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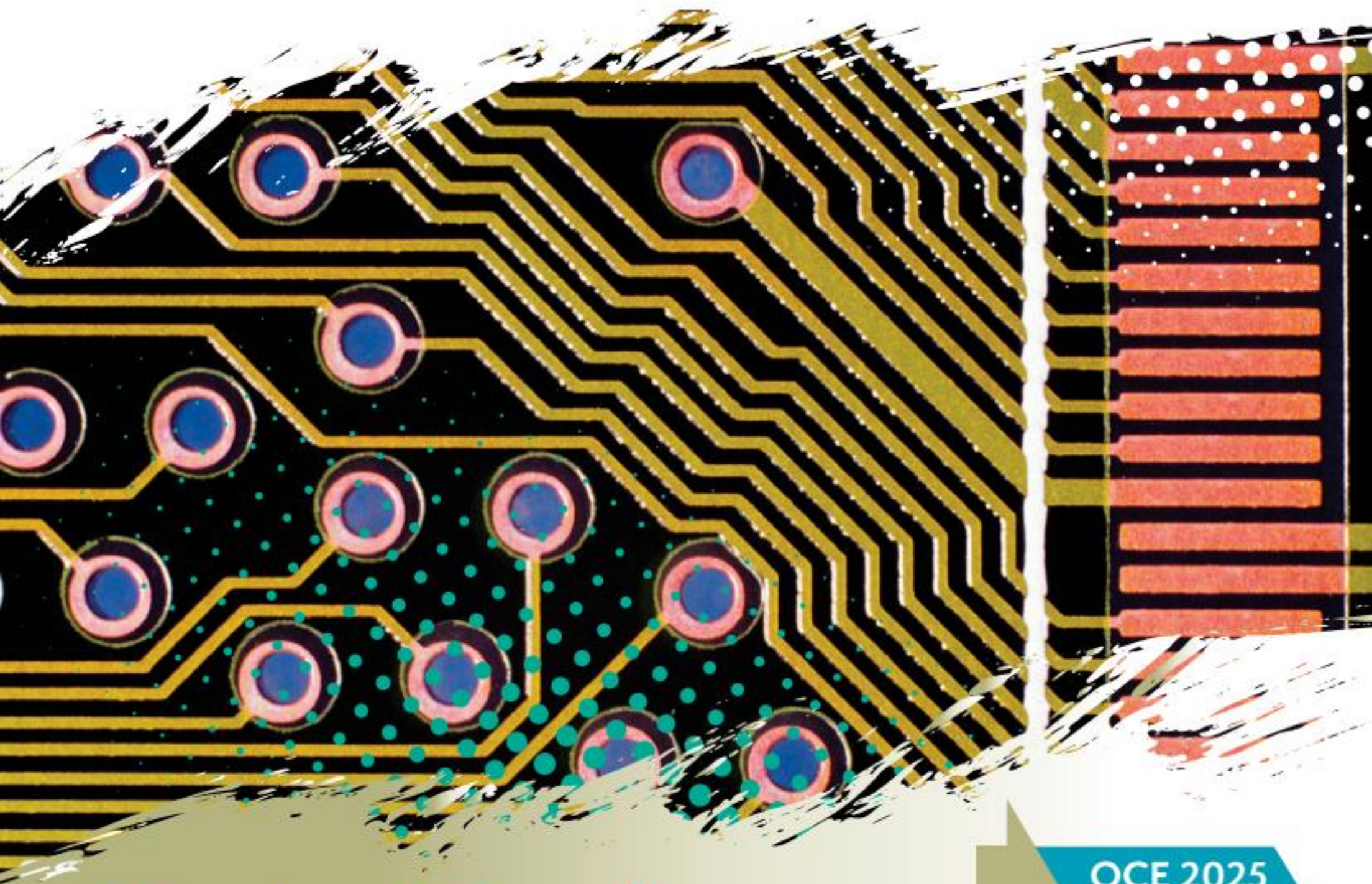

Student Book

QCE 2025 Physics SYLLABUS

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STUDENT BOOK

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Series Publisher: Alicia Brown
Editorial Development Manager: Leanne Peters
Project Manager: Jenna Tinkle
Delivery Manager: Jaimi Kuster
Development Editors: Shirley Melissas, Natalie Orr, Marta Veroni, Caroline Hunter
Editor: Mark Gadd, Newgen KnowledgeWorks
Designer: Anne Donald, Newgen KnowledgeWorks
Rights & Permissions Editors: Alice McBroom, Minjin Song
Proofreader: Michael Lynch, Newgen KnowledgeWorks
Indexer: Sue Leech, Newgen KnowledgeWorks
Illustrators: DiacriTech, Newgen KnowledgeWorks
Desktop Operator: Jit-Pin Chong
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Syllabus
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For the most current syllabus versions and curriculum information please refer to the QCAA website https://www.qcaa.qld.edu.au/

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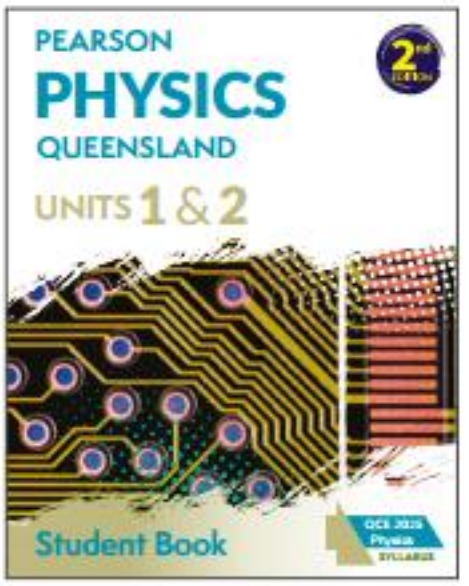

Writing and development team

We are grateful to the following people for their time and expertise in contributing to the *Pearson Physics Queensland Units 1 & 2* 2nd edition.

Matthew Crank
Academic Leader, Head of Physics, Science Teachers Association of Queensland – Vice President, Australian Science Teachers Association – Queensland Delegate
Series Consultant, Author and Reviewer

Dr Kristen Matherson
Senior Science Teacher
Associate Series Consultant, Author and Reviewer

Bryonie Scott
Learning Designer and Science Communicator
Queensland Physics Subject Lead, Author

Daniela Nardelli
Senior Science Teacher
Subject Lead

Doug Bail
Education Consultant
Skills & Assessment Book Lead Author

Mark Baker
Head of Science (Physics)
Queensland Physics Series Consultant, Lead Author

Kaitlin Jobson
Head of Physics
Author

Craig Tilley
Science Writer and Assessor
Author

Contributing authors
The publisher wishes to acknowledge and thank the following authors of the first edition of this series:

Associate Professor David Geelan FACE
Sam Trafford
Alan Allinson
Keith Burrows
Rob Chapman
Ann Conibear
Jacinta Devlin
Steven Eddy
Tracey Fisher
Carmel Fry
Melissa Gould
Brianna Hore
Errol Hunt
John Joosten
Greg Moran
Gregory White

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Penny Lee
Svetlana Marchouba
Kevin Richard
Professor David F Treagust PhD FRSC FRSB FAERA
Dr Trish Weekes

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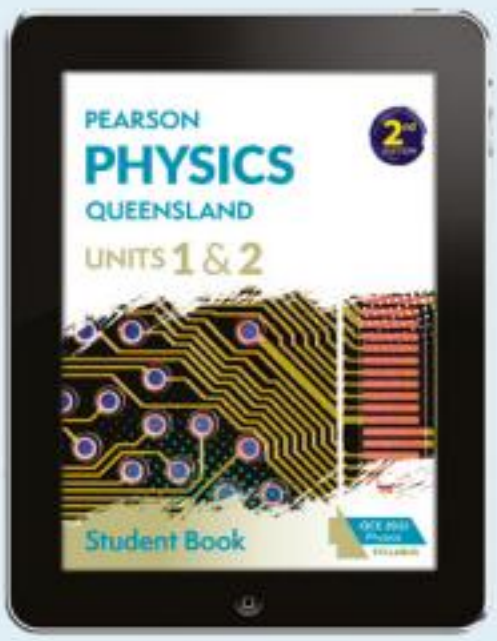

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How to use this book

PEARSON PHYSICS QUEENSLAND STUDENT BOOK UNITS 1 & 2 2ND EDITION

Pearson Physics Queensland Student Book Units 1& 2 2nd edition has been written to the 2025 QCAA Physics Syllabus. This book includes an additional Skills and Assessment Toolkit online as well as a depth of additional resources, to support every aspect of teaching and learning. Explore how to use this book below.

Design

The best-practice literacy and instructional design supports all learners.

A simple-to-navigate predictable design enables ease of use. The high-quality, relevant photos and illustrations assist students' understanding of concepts.

Chapter 1

The Skills and Assessment Toolkit provides support across the Science Inquiry Skills and Assessment requirements. The material is presented as a handy reference to enable confident, complete coverage of the syllabus across the course. Reworked and fully updated to meet the evolved requirements of the revised QCE 2025 Syllabus, and to respond to the needs of teachers and students.

Chapter opener

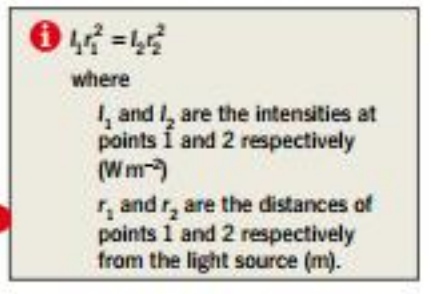
The syllabus subject matter addressed in each chapter is clearly listed, and mapped to the modules in which the content is addressed.

Module opener

Module openers outline the key concepts and skills to be developed and link to the syllabus subject matter listed in the Chapter opener.

Science as a human endeavour

Science as a human endeavour (SHE) features provide stimulus for the Research investigation. The SHE features are structured to develop the foundational skills relevant to supporting the relevant Science inquiry skills through the lens of Science as a human endeavour, providing a suitable foundation from which students can launch into Research investigation IA3 and draw upon building proficiency for Assessment objectives 1, 2 and 3.


$I_1 r_1^2 = I_2 r_2^2$
where
I_1 and I_2 are the intensities at points 1 and 2 respectively ($W m^{-2}$)
r_1 and r_2 are the distances of points 1 and 2 respectively from the light source (m).

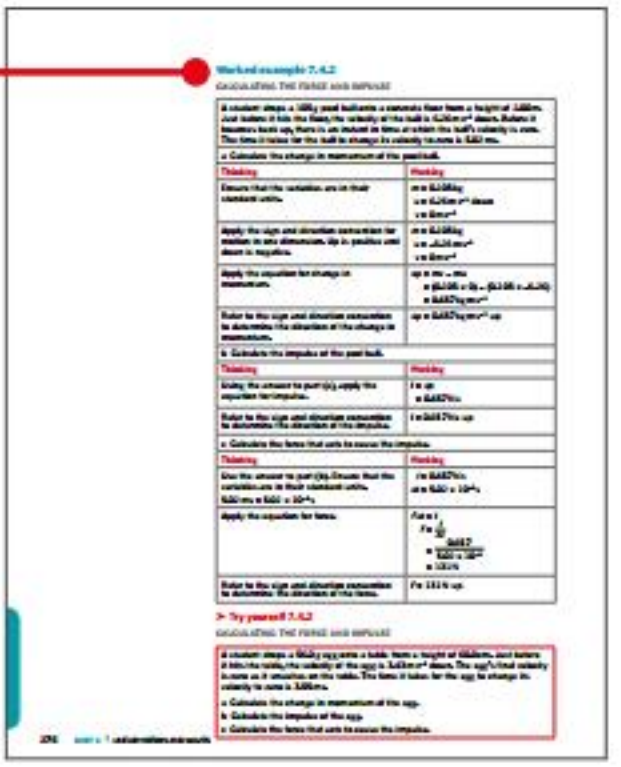
Highlight box

Highlight boxes focus on important information such as key definitions, formulas and salient points.

How to use this book

Worked examples

Worked examples use sequential steps of thinking and working to model calculations and problem-solving, step-by-step. Each Worked example is followed by a Try yourself task where students apply their learning to a mirrored problem. Fully worked solutions to all Try yourself problems are available online on *Pearson Physics Queensland Units 1 & 2 2nd edition* eBook.



Skillbuilders

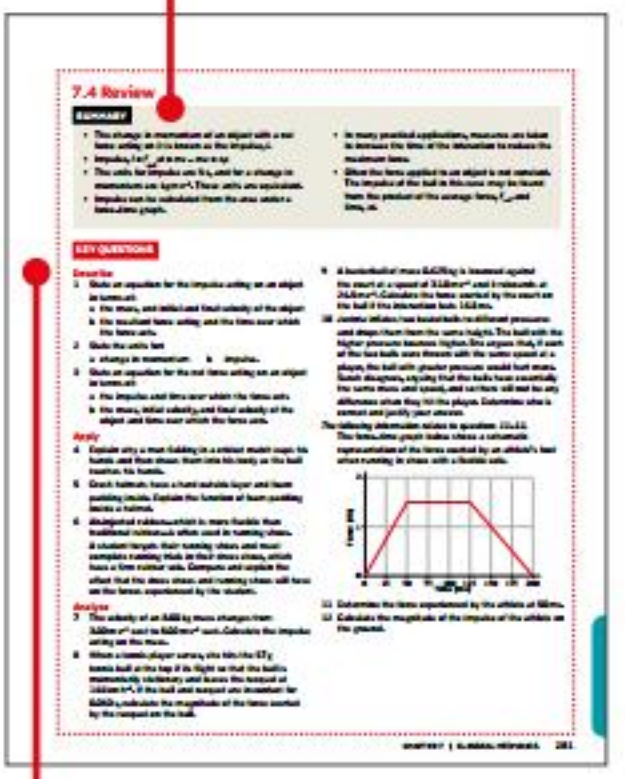
Skillbuilders outline a method or technique. Each is instructive and self-contained. Skillbuilders step students through the skill to support science application required when analysing or utilising knowledge.

Practical manual

Practical investigations offer students the opportunity to develop, practise, and refine their Science inquiry skills. These activities involve gathering primary data to analyse and respond to scaffolded or open-ended science tasks, supporting deeper understanding and proficiency in scientific methods. Additionally, these tasks allow teachers to formatively assess students' Science inquiry skills and set students up well with the insights for Student experiment IA2, pertinent to Assessment objectives 1 to 6. All Practical investigations have been trialled and tested to ensure they can be safely performed and yield effective results. Full risk assessments and additional support are provided in the eBook.

Module summary

Each module concludes with a summary to help students consolidate key points and concepts.



Module review

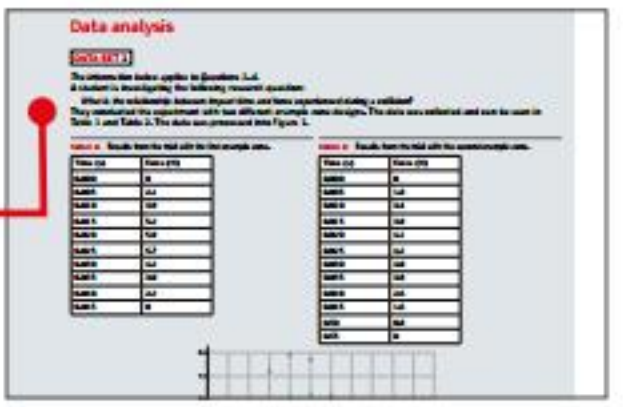
Key questions are provided to test students' understanding of concepts of the module. Questions are presented under the three Assessment objectives of Describe, Apply and Analyse. This structure allows students to demonstrate their progress in developing an understanding of the science subject matter.

Chapter review

Each chapter finishes with a list of key terms covered in the chapter, and a set of multiple choice and short response questions, reflecting the style and experience of the External Assessment (EA). These questions are organised under the four Assessment objectives for the subject matter: Describe, Apply, Analyse and Interpret.

Data analysis

Data analysis tasks at the end of most Chapter reviews provide an opportunity to respond to questions that use a range of qualitative and quantitative data relevant to that subject matter. The Data analysis tasks reflect the approach taken in the Data Test IA1 and align with the Assessment objectives 2, 3 and 4.



Unit review

Each Unit finishes with a comprehensive set of exam-style questions, including multiple choice, short answer and extended response in the style of the External Assessment (EA). These review tasks assist students to draw together their knowledge and understanding of the whole unit.

Glossary

Key terms are shown in **bold** throughout the Student Book and are listed at the end of each chapter. A comprehensive glossary at the end of the book defines all the key terms and the glossary aligns with the syllabus context.

Answers

Comprehensive answers and fully worked solutions for all Module review tasks, Try yourself, Science as a human endeavour, Chapter reviews and Unit reviews are provided via the eBook.

Icons

Go To icons make important links to relevant content within the student books in the course. The Go To icons indicate:

GO TO ➤

- when a Practical investigation would be suitable to engage with
- where support is available for skills and assessment tasks in Chapter 1 of your eBook.

Every Practical investigation is supported by a complementary **SPARKlab** alternative practical.

Pearson

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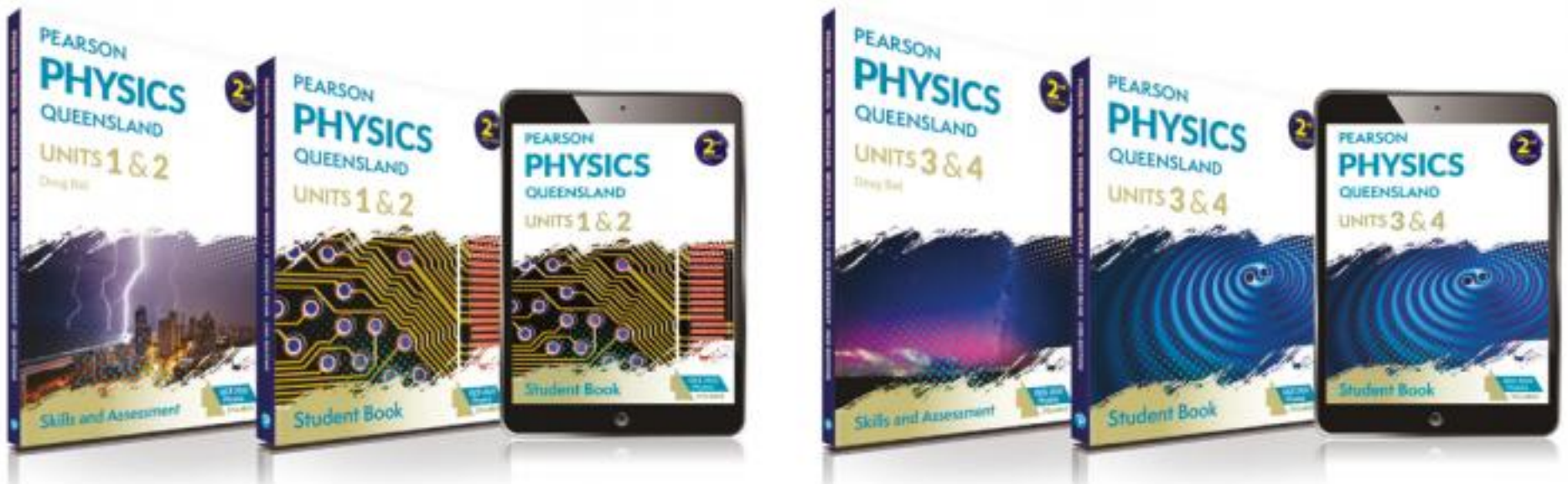

Student book

- The expert author team has delivered the same high-quality content you can trust, in the streamlined new edition for Queensland science classrooms.
- New, enhanced, and updated features that make the new second edition Student Books stand out:
  - New Science as a Human Endeavour sections
  - New Data Analysis tasks at the end of each Chapter review
  - Enhanced and updated Skills and Assessment Toolkit
  - Enhanced question sets
  - Updated Practical Manual of Practical Investigations
  - Updated Unit reviews and glossary.

Skills and assessment book

- The Skills and Assessment Book gives students the edge in preparing for all forms of assessment.
- It has been updated and refined to respond to the revised syllabus, and specifically provide opportunities to consolidate, develop and apply subject matter and Science inquiry skills. This resource features:
  - An updated Toolkit
  - Key knowledge summaries
  - Worksheets
  - Practical investigations and guidance
  - Assessment practice
  - Exam-style topic review sets.

eBook

Learner eBook access includes:

- Student book content
- Access to digital resources
- Fully worked solutions.

Teacher eBook access includes:

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- Practical investigation expected results, common mistakes, suggested answers and full safety notes and risk assessments
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CHAPTER

01 Physics skills and assessment toolkit

This chapter provides important information and support in the study of the QCAA Physics General Senior Syllabus for Units 1 to 4.

The Physics skills and assessment toolkit is designed to be used as a reference tool. It should be consulted on a need-to-know basis, where relevant, during this course of study. It is not intended that this chapter be worked through as a whole.

This chapter focuses on providing support and guidance in:

- **Development and application of scientific skills**
  - Mathematical and statistical processes used in physics
  - SI units
  - Visual representations
  - Graphical representations
  - Measurement errors and uncertainty.
- **Completing the assessment tasks**
  - Data test
    - Preparation in skill development.
  - Student experiment
    - Forming a relevant research question
    - Justifying experiment modifications
    - Developing a methodology
    - Finding sufficient, relevant data
    - Interpreting and analysing evidence
    - Evaluating experimental process
    - Scientific writing and representations
    - Referencing sources
  - Research investigation
    - Developing a research question from a claim
    - Collecting relevant and sufficient evidence to answer research question
    - Identifying and analysing trends, patterns, relationships in the evidence
    - Evaluating the quality and limitations of the evidence
    - Evaluating the research process
    - Scientific writing and representations
    - Referencing sources

Assessment

In Units 1 and 2, students are required to complete at least two and no more than four assessment tasks developed by the teacher. At least one assessment task must be completed per Unit. In preparation for Physics Units 3 and 4, teachers may choose to mirror some of the assessment requirements of Units 3 and 4 in assessing Units 1 and 2.

The support material in this chapter is based on requirements in Units 3 and 4 and relates to the following assessments:

- Data test Internal Assessment IA1
- Student experiment Internal Assessment IA2
- Research investigation Internal Assessment IA3

Chapter organisation

The chapter is arranged in three parts:

- Part A: Working scientifically
- Part B: Student experiment
- Part C: Research investigation.

An outline of these parts is provided below.

QCAA Physics Syllabus objectives

- Describe ideas and findings
- Apply understanding
- Analyse data
- Interpret evidence
- Evaluate conclusions, claims and processes
- Investigate phenomena.

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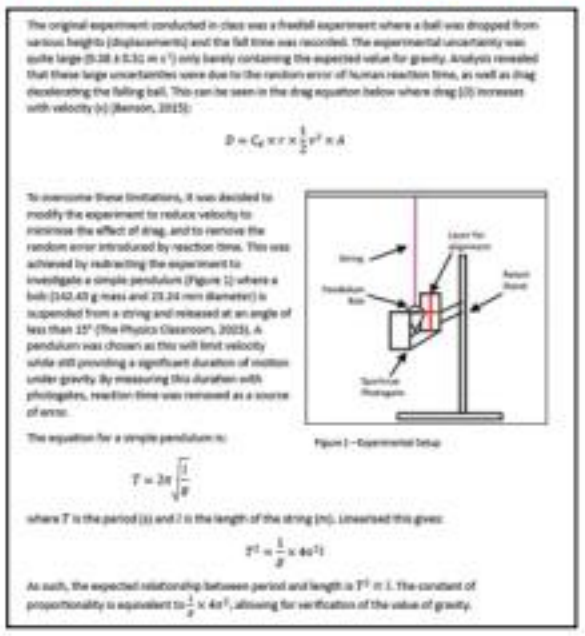
Part A: Working scientifically

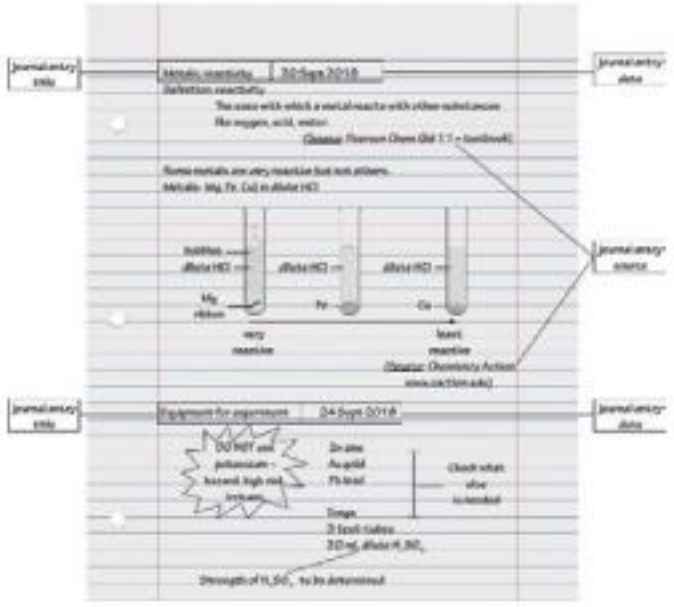
Part A focuses on basic mathematical skills and their applications. It features many Worked examples and opportunities to apply these examples yourself. These skills are assessed, directly and indirectly, in assessment tasks and to analyse data in practical investigations. Part A focuses on skills for the Data test, and experiments. These skills are useful when completing sections of the Student experiment, Research investigation and the Examination.

Refer to the following outline of *Part A: Working scientifically*, to learn, revise and practise the skills in the areas in which you need help.

Module	Look here for	eBook page
1.1 Physics	- areas of physics - the work of scientific research	e7
1.2 Orders of magnitude	- scientific notation - transforming decimal notations to scientific notation - converting between scientific notation and scientific units, orders of magnitude and prefixes - SI prefixes - examples of calculations	e14
1.3 Mathematical basics for physics	- examples of maths used in physics - analysing straight line graphs - trigonometric ratios and logarithms	e20
1.4 Units	- measurement and units - correct use of unit symbols - SI prefixes - unit conversions	e28
1.5 Measuring precision and accuracy using uncertainties and percentage error	- explanations of the terms: 'uncertainty', 'error', 'accuracy' and 'precision' - causes of errors - calculations with uncertainty and error - writing measurements with uncertainty and error values - writing measurements and calculations to the correct significant figure - determining the absolute uncertainty of a value - converting between absolute and percentage uncertainties - calculating a value along with the associated uncertainty	e33
1.6 Tables and graphing	- arranging and recording data in tables - converting data from tables to graphs - types of graphs—scatterplots, line graphs, bar and column graphs, pie charts - outliers and how they are represented on graphs - representing missing data on graphs	e50
1.7 Data analysis	- calculating mean, median, mode and range - regression, linear regression, coefficient of determination and *r*-values - linearising data - three line graphs	e58
1.8 Scientific writing	- writing scientifically - developing scientific representations - maintaining a science journal - referencing sources - in-text citations - using AI in research and writing - plagiarism - referencing AI sources - multimodal presentations	e72

Part B: Student experiment





Part B focuses on the student experiment. This internal assessment task requires students to follow the full scientific method over an extended and defined period of time. Students develop their own research question to investigate, based on an identified experiment related to Unit 3 subject matter.

Part B supports you through all aspects of the student experiment. The QCAA objectives and instrument-specific marking guide (ISMG) for the assessment are explained.

Part B provides examples of how to **modify (extend**, **refine** or **redirect)** the initial experiment to write an experimental research question. Included is a step-by-step guide to evaluate the quality of your question and explanations of scientific methodology. Part B also covers data types, data collection and analysis of data to draw valid conclusions, including how to evaluate the quality of data including its reliability and validity, and how to link these to logical improvements and extensions. Also provided is support in writing-up your scientific report, covering writing conventions and referencing sources.

Refer to the following outline of *Part B: Student experiment*, to learn, revise and practise your skills in the areas in which you need help.

Module	Look here for	eBook page
1.9 Syllabus requirements	- instrument-specific marking guide (ISMG) - assessment objectives - suggested report structure - length requirements	e83
1.10 Forming	- establishing background information - developing a rationale - defining variables - developing the research question - evaluating the research question - justifying the question modification - putting it all together: sample report	e86
1.11 Finding	- determining the risk assessment - managing risk - considering environmental and ethical issues - collecting sufficient and relevant raw data - collecting data electronically - putting it all together: sample report	e95

Module	Look here for	eBook page
1.12 Analysing	- presenting the data - processing data using mathematical techniques - identifying patterns, relationships, trends in data - interpreting results - identifying uncertainty and limitations in the evidence - putting it all together: sample report	e105
1.13 Interpreting and evaluating	- drawing a conclusion that is linked to the research question - discussing reliability and validity - identifying improvements and extensions to the research - putting it all together: sample report	e112

Part C: Research investigation

Part C focuses on the research investigation. This internal assessment task requires students to gather secondary evidence on a research question. It is completed over an extended and defined period of time. Students develop their own research question to investigate, based on a claim related to Unit 4 subject matter.

Part C supports you through all aspects of the research investigation. The QCAA objectives and instrument-specific marking guide (ISMG) for the assessment are explained.

Part C assists with writing your research question. It considers examples of claims, and how to analyse claims for context and guides you in developing your own research question. You will be guided in writing a specific and relevant research question that encompasses a small sub-section of the claim and is linked to Physics syllabus concepts. You will consider the information on locating and evaluating suitable secondary sources for the research, including identifying errors and relationships in data and assessing validity. You will learn how to formulate a justified conclusion and describe improvements and extensions. There is support for writing your scientific report, including guidance on scientific writing style and the structure of the report.

Refer to the following outline of *Part C: Research investigation*, to learn, revise and practise your skills in the areas in which you need help.

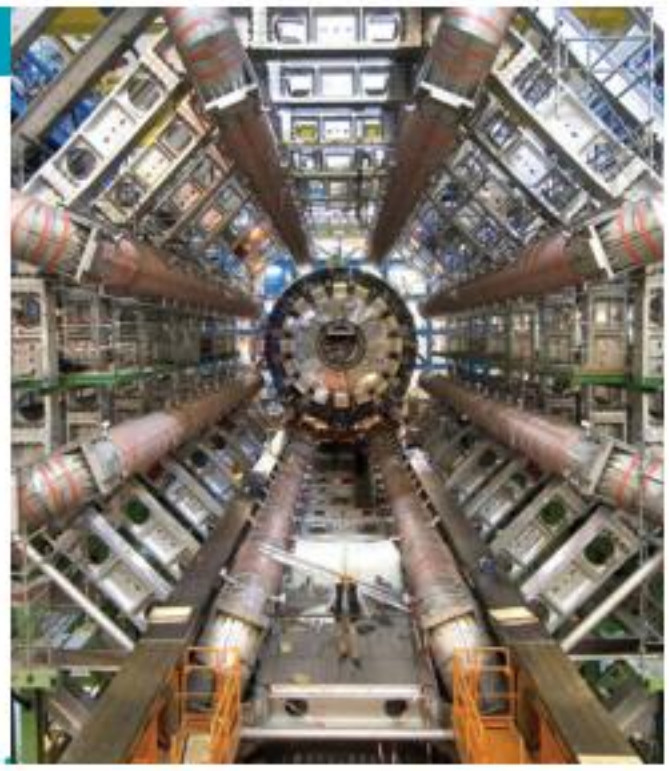
Module	Look here for	eBook page
1.14 Syllabus requirements	- instrument-specific marking guide (ISMG) - assessment objectives - suggested report structure - length requirements	e117
1.15 Forming and finding	- analyse a claim - identify variables and measurable terms in the claim - examples of claims and research questions developed from them - guidelines for developing a question - develop a research question - refining a research question - putting it all together: sample report	e119

Module	Look here for	eBook page
1.16 Analysing	- collecting sufficient and relevant evidence - identifying trends, patterns, relationships in the evidence - assessing limitations of the evidence - putting it all together: sample report	e131
1.17 Interpreting	- assessing if the evidence justifies the claim - presenting an argument whether the claim is justified - reaching a conclusion about the claim - putting it all together: sample report	e136
1.18 Evaluating	- evaluating the quality of the evidence - suggesting any extrapolations of the claim - suggesting any improvements/extensions to the investigation - putting it all together: sample report	e138

1.1 Physics

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand and appreciate that physics is a fundamental science, and its capacity to ask the 'big' questions makes it incredibly interesting
- understand that science provides a systematic approach for comprehending the world.
- explain the difference between scientific models, theories, laws, principles and facts
- understand that physics uses natural laws, theories, models and principles to describe real phenomena
- appreciate that physics uses mathematics
- recall the major areas of physics
- explain how a vast number of professions use some aspect of physics
- appreciate that physics is a dynamic and evolving branch of science, and that not every problem has been solved



WHAT IS PHYSICS?

Science is a human endeavour to understand the world and the known universe. It is one method of many used to develop knowledge. This knowledge is continually refined and redefined. Science follows a **methodology** to observe, test, measure, analyse and evaluate natural **phenomena** in a way humans can understand and construct meaning. There is no single **scientific method**; however, it is a cyclical process including observation of natural phenomena, questioning, hypothesising and predicting, experimentation and gathering **data**, refining and altering all previous elements, and theorising.

Today, all scientific disciplines are expanding into new frontiers. The number of divisions and fields in physics is ever-increasing, and the relationship between disciplines is becoming more intertwined. Innovations today are crossing the traditional barriers between technology, chemistry, physics and biology of the past 100 or so years.

Physics is the study of motion, forces and energy. It is the most **fundamental** science. It deals with the laws, theories and principles governing force, energy and motion across all imaginable scales throughout the universe. These range from the interactions between particles that make up the individual protons and neutrons inside every atomic nucleus, to the motions of galaxies that comprise the universe itself. Physics is full of history and amazing discoveries and famous scientists, such as the scientists in Figure 1.1.1, who made numerous contributions to modern physics.

FIGURE 1.1.1 The fifth Solvay conference held in 1927 was perhaps the greatest convergence of physicists and chemists in the 20th century. Back row: Piccard, Henriot, Ehrenfest, Herzen, De Donder, Schrödinger, Verschaffelt, Pauli, Heisenberg, Fowler, Brillouin. Centre row: Debye, Knudsen, Bragg, Kramers, Dirac, Compton, de Broglie, Born, Bohr. Front row : Langmuir, Planck, Skłodowska-Curie, Lorentz, Einstein, Langevin, Guye, Wilson, Richardson.

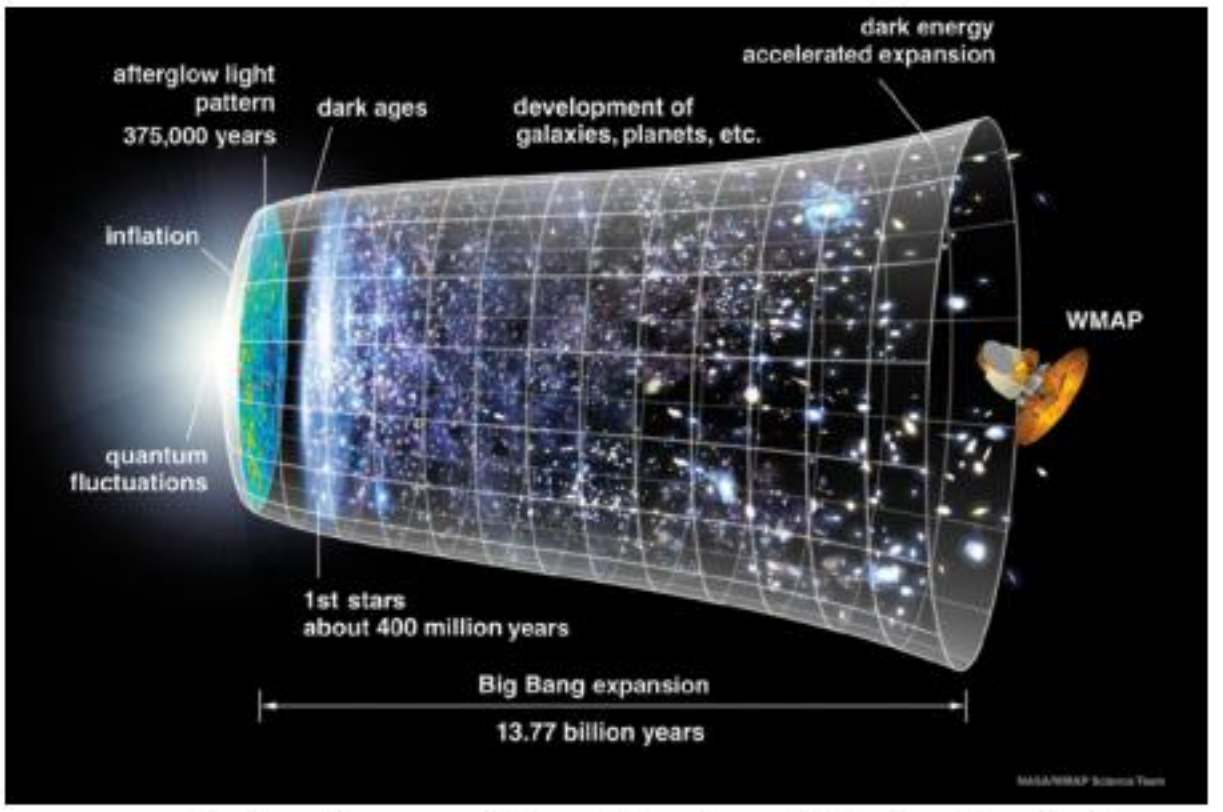


FIGURE 1.1.2 Fourteen billion years of history of the universe. The Big Bang theory for the creation of the universe is shown on the far left. The present-day universe is on the far right, along with a satellite called the Wilkinson Microwave Anisotropy Probe (WMAP), which collected data to help piece together the theory.

FIGURE 1.1.3 An artist's illustration of a planet being destroyed as it orbits a very strange star in our galaxy called 'Tabby's Star'. The light from this star appears to randomly fluctuate and currently defies all known explanations. The latest theory is that it is likely due to an uneven dust cloud moving around the planet.

The wonder of physics lies in its ability to ask the 'big' questions, such as:

- Where did the universe come from? To date, our best theory is the Big Bang theory (Figure 1.1.2).
- Does the universe have an end?
- Are we alone in the universe, or is the universe full of intelligent, alien civilisations (Figure 1.1.3)?
- What is matter made up of?
- Is there a single theory or equation that can describe everything?

Interestingly, the answers to these questions are still unknown, but perhaps you will be inspired to try to answer them.

Physics uses the language of mathematics to make logical sense of the universe, using models and theories to explain natural **phenomena**. If it is not supported by observations and experiments, then the model or theory is rejected and a new theory takes its place.

If a ladder showing the level of fundamental explanations of the natural world is made, as in Figure 1.1.4, physics would be on the second-bottom rung, second only behind mathematics in the way it can describe the basic interactions in the natural world.

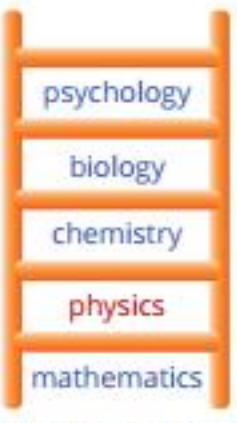


FIGURE 1.1.4 Physics uses mathematics to explain how the natural world works. Chemistry uses the laws of physics to explain matter and the interactions of matter, whereas biology and psychology use the products of chemical reactions to explain the living world.

All other sciences have their basis in some aspect of physics. For example, an understanding of how chemical bonding works can be explained by the laws of electrostatic forces and the theory of quantum mechanics.

Physics had its origins more than 5000 years ago when the ancient Babylonians recorded the positions of stars, planets and comets, so it is generally considered that astronomy (a major branch of physics) is the oldest science. In the 21st century, physics is used in almost every aspect of science. One of the newest branches of physics is gravitational wave astrophysics, which originated with Albert Einstein in 1916 and was only confirmed with data in 2016.

Since Einstein's time, physicists have refined their understanding of the universe. Most of the time, physicists have used that body of knowledge to improve the lives of humans and the other organisms that share this planet.

DOMAINS AND BRANCHES OF PHYSICS

Physics can be roughly divided into four domains, depending on the size of the objects that are interacting and how fast they travel (Figure 1.1.5). Each domain has several branches stemming from historical advances in thinking or in experimental results.

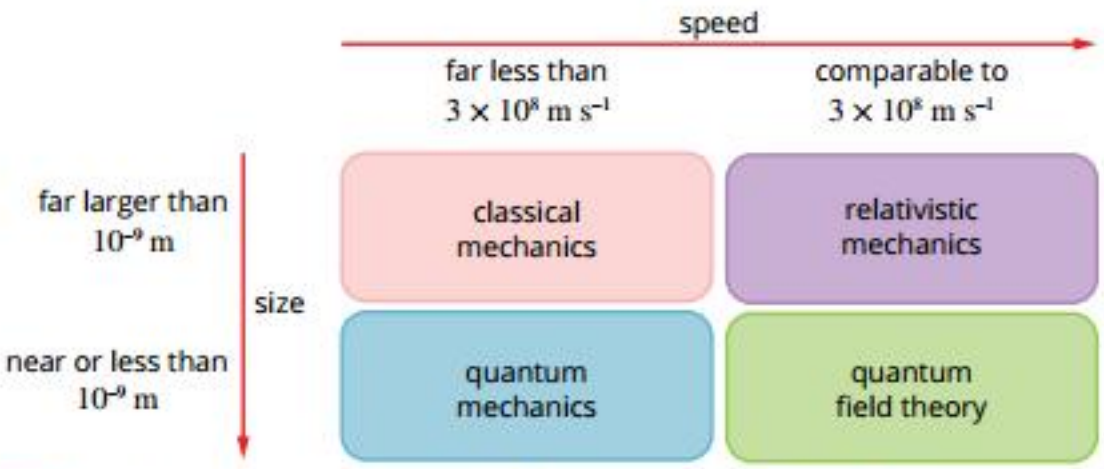


FIGURE 1.1.5 The four domains of physics describe matter and energy of various sizes moving at various speeds.

Classical mechanics is the first domain of physics. It deals with the forces, energy, gravity and motion of everyday objects, planets, stars and galaxies as long as they are not moving at close to the speed of light. Most of the physics you will study in Years 11 and 12 comes from classical mechanics, or the view of the universe given to us by Isaac Newton from the 17th century.

Quantum mechanics is the second domain of physics. In Units 3 and 4 you will touch on the 'modern' view of physics by exploring quantum mechanics, or the strange world of light and very small particles such as the atom and its constituents. Physicists formulated these theories in the early 20th century. Quantum mechanics has been described as the most accurate and precise scientific theory ever written, but it does not include gravity in its formulation.

Relativistic mechanics is the third domain of physics. In Units 3 and 4 you will explore part of the bizarre and counterintuitive world of relativistic mechanics brought to us by Albert Einstein also at the beginning of the 20th century. Relativistic mechanics deals with the motion, gravity and energies of all objects larger than an atom when they travel at speeds approaching the speed of light.

Quantum field theory (QFT) is the fourth domain of physics. It is a combination of the theories of the very small (quantum mechanics) and very fast (relativistic mechanics). The mathematics of QFT is beyond high school level and you will not explore this in any detail.

To date, nobody has come up with a successful unification or grand unified theory (GUT) of these four aspects of physics. The GUT would have to describe the entire universe at every scale and speed, and make measurable predictions that can be tested with experiments. In other words, the physics of very small objects moving very fast under gravity is yet to be understood. For example, at the very centre of a black hole, known as the singularity, the laws of physics break down because we do not yet understand how small particles behave under the influence of strong gravity.

String theory describes everything in the universe as a tiny vibrating string of energy (Figure 1.1.6.) It is a possible GUT, but so far has not been used to make measurable predictions.

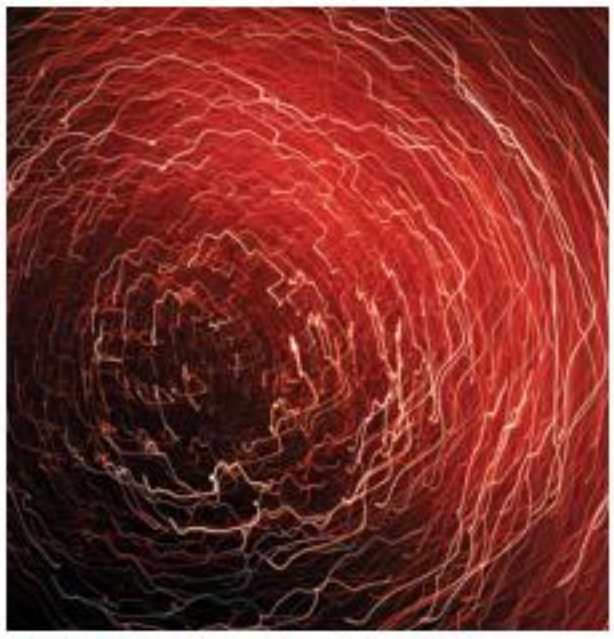


FIGURE 1.1.6 String theory describes everything in the universe as a tiny, vibrating string whose frequency determines if the object is a particle of matter or a wave of energy.

The major branches of physics are mechanics, thermodynamics, atomic and nuclear physics, electromagnetism, waves and relativity.

Using the four domains of physics, Figure 1.1.7 shows all of the branches of physics you will study in this course. These branches are briefly explained in Table 1.1.1, which also lists some of the famous people who worked in them.

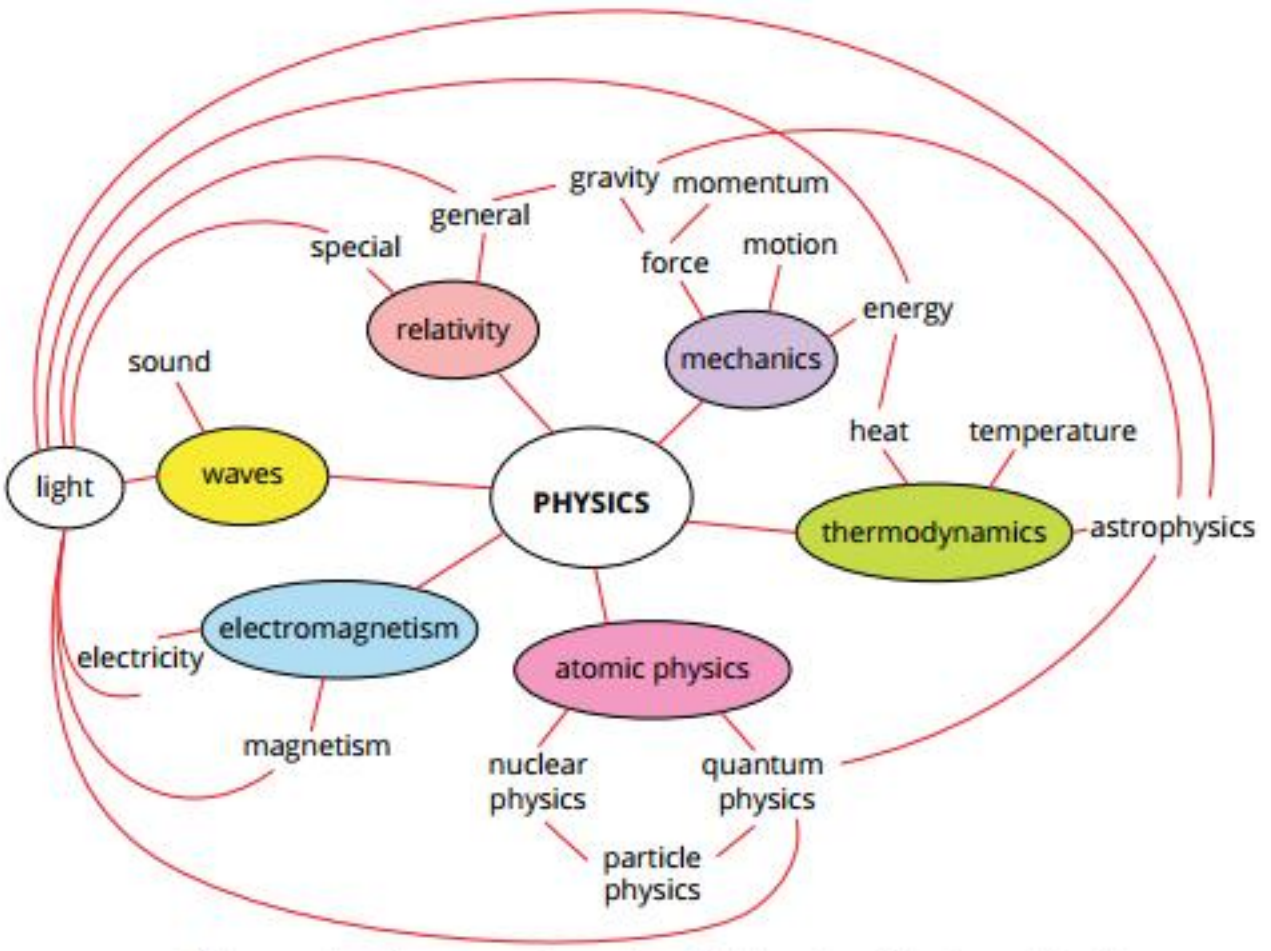


FIGURE 1.1.7 This non-exhaustive concept map shows the branches of physics and the links between their concepts.

TABLE 1.1.1 A brief description of the branches of physics

Branch of physics	What it explains	Famous people involved in the branch
mechanics	motion, forces, gravity and energy	Isaac Newton, Galileo, Nicolas Copernicus, Johannes Kepler, Robert Hooke, Blaise Pascal
thermodynamics	temperature, heat, matter, and the combination of these to provide motion	James Joule, Ludwig Boltzmann, Sadi Carnot, Felix Wankel, Rudolf Diesel
waves	sound, light and how energy moves from one location to another	Isaac Newton, Max Planck, Christiaan Huygens, Christian Doppler, Heinrich Hertz
electromagnetism	electricity, current, voltage and magnets, motors and generating electrical power	James Clerk Maxwell, Michael Faraday, Nikolai Tesla, Andre-Marie Ampere
atomic and nuclear physics	the atom, nucleus, particles that make up the nucleus, and how they interact with other matter and light	Marie Curie, Albert Einstein, Niels Bohr, Ernest Rutherford, Max Planck, Stephen Hawking, Richard Feynman, Peter Higgs
relativity	how the laws of physics above change when particles move very fast or when particles become close to a very large but dense object	Albert Einstein, Galileo, Hendrik Lorentz

THE ROLE AND WORK OF A PHYSICIST

Those who study physics are typically known as physicists. Physicists use models, theories and laws to explain the universe in terms of mathematical symbols. To check and refine their theories, they carry out experiments, collect data and analyse their results. Their theories are then changed or refined according to their results. The foundation of all sciences, including physics, is scientific research. Scientific research works in the unknown to develop new understandings. To build evidence, it may take years and many experiments. In interpreting scientific evidence, scientists endeavour to establish models, **theories**, **laws**, **principles** and facts. These are illustrated in Figure 1.1.8. It is important to note that all these deductions change over time as knowledge develops.

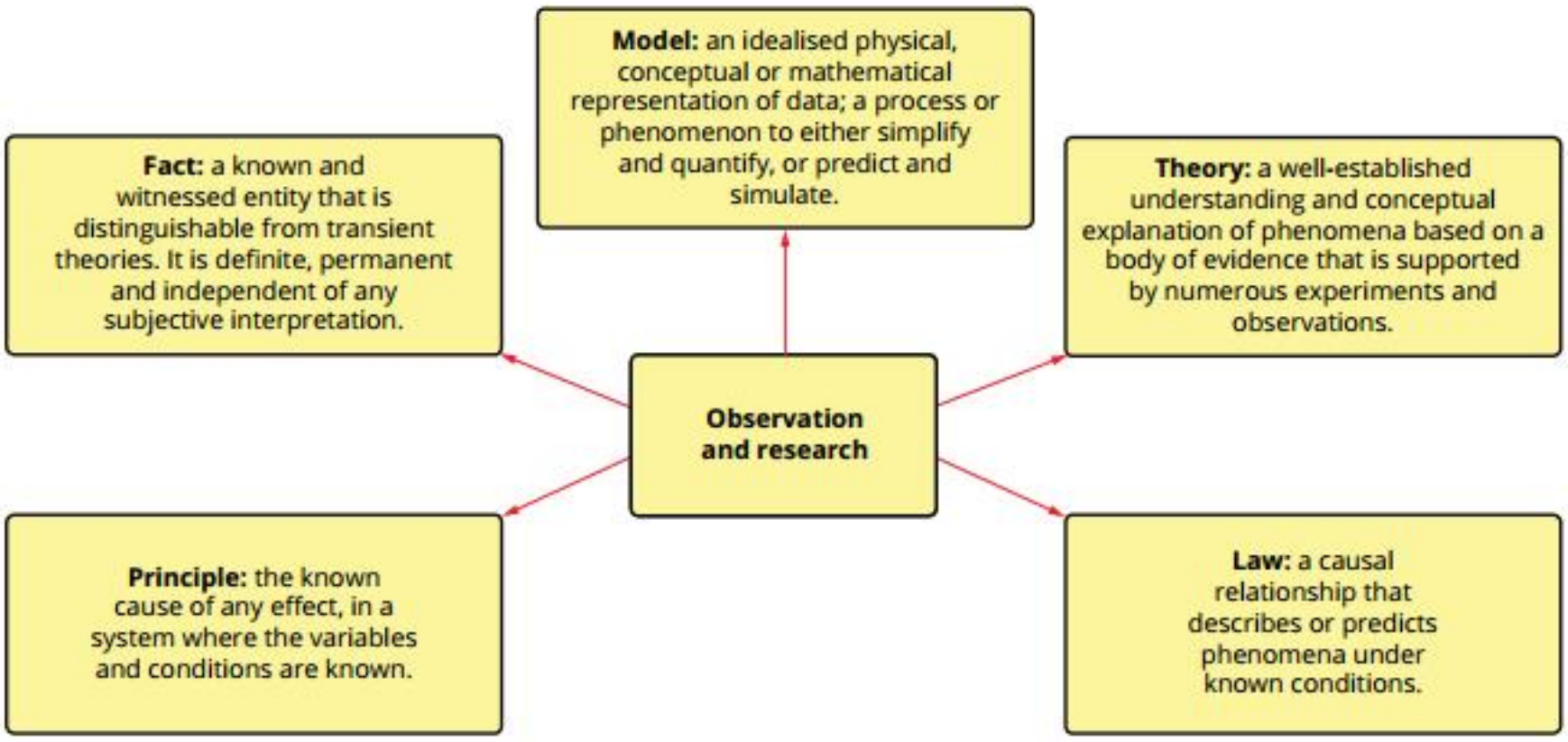

Model: an idealised physical, conceptual or mathematical representation of data; a process or phenomenon to either simplify and quantify, or predict and simulate.
Fact: a known and witnessed entity that is distinguishable from transient theories. It is definite, permanent and independent of any subjective interpretation.
Theory: a well-established understanding and conceptual explanation of phenomena based on a body of evidence that is supported by numerous experiments and observations.
Observation and research
Principle: the known cause of any effect, in a system where the variables and conditions are known.
Law: a causal relationship that describes or predicts phenomena under known conditions.

FIGURE 1.1.8 Scientific research and observations are used to develop facts, principles, laws, theories and models.

A physics **model** is a way of visualising a particular physical phenomenon that is quite often impossible to imagine in the real world. It may or may not be entirely correct.

Examples of models:

- the wave model of light
- the particle model of light.

A physics **theory** is a model that is more mathematically rigorous. It uses mathematical formulas to predict the behaviour of the model. Again, it may or may not be correct, but the phenomenon it describes is real.

Examples of theories:

- Newton's theory of gravity
- Einstein's general theory of relativity.

A physical **law** is a general statement that is found to be experimentally true over a large range of observed phenomena. It describes how nature behaves. A principle is a law but is more specific in its scope.

Examples of laws:

- The three laws of motion
- Archimedes' principle.

Physics uses mathematics to explain the natural world in terms of models, theories, laws and principles.

The advances in scientific endeavours as well as innovations have seen a significant increase in multiple scientific specialities and disciplines working together. When more than one discipline is required to solve a problem or develop an innovation, it is said to be transdisciplinary. Transdisciplinary approaches to scientific endeavours form the heart of STEM.

As the world changes, science, technology, engineering and maths (STEM) integrate numerous disciplines into vocational roles. There are numerous reports every year outlining that most future professions will be STEM related. For example, a recent report from a multinational business organisation indicated that jobs in 75% of growing and future industries will require STEM qualifications.

A STEM qualification fosters skills in areas such as creativity and critical thinking, and is highly regarded in public and private businesses.

Physics is the most fundamental science and explains how the laws of nature work, so anyone that uses technology is using some aspect of physics. Examples of some of the many occupations that use physics either directly or indirectly are given in Table 1.1.2 and Figures 1.1.9 to 1.1.11.

TABLE 1.1.2 Examples of the branches of physics used in various professions

Profession	Aspect of physics used
archaeologists	nuclear physics used in carbon dating
astronomers	all aspects of relativity, light and gravity
climate scientists	forces, thermodynamics
dentists	forces, thermodynamics, sound and light
doctors	forces, nuclear physics, atomic physics, waves, electromagnetism (see Figure 1.1.11)
electricians	electromagnetism
engineers (civil, mechanical, electrical, sound, optical, aerospace, materials, mining)	all aspects of physics
geologists	gravity, thermodynamics, atomic physics

FIGURE 1.1.9 A medical physicist prepares a patient for a scan in a magnetic resonance imaging (MRI) machine.

FIGURE 1.1.10 Police use physics to determine the speed and direction of vehicles involved in traffic accidents.

FIGURE 1.1.11 Physics plays a central role in the animation of many video games and developers need to know the laws of physics to accurately represent motion in their games.

1.1 Review

SUMMARY

- Science is a systematic approach to develop knowledge through testable explanations and repeatable means.
- Physics is a dynamic and evolving branch of science.
- Physics uses mathematics as its language.
- A physics model is a visual way of describing an invisible natural phenomenon.
- A physics theory is a mathematical description of a natural phenomenon.
- A law of physics is a general statement that is found to be experimentally true over a large range of observations.
- A physics principle is a law of physics that is more specific in its context.
- Classical mechanics, quantum mechanics, relativistic mechanics, and quantum field theory are the four domains of physics.
- Major branches of physics are mechanics, thermodynamics, atomic and nuclear physics, electromagnetism, waves and relativity.
- A vast number of professions use some aspect of physics.

Part A will consider the basic mathematical and data skills and applications that will be required for the student experiment, research investigation, data test, and practicals.

1.2 Orders of magnitude

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- convert numbers to and from scientific notation
- convert between various units of the same type using SI and some non-SI units.

SCIENTIFIC NOTATION

In scientific research and literature, measurements are often written in **scientific notation** to overcome confusion or ambiguity when displaying numbers with magnitude, for example 2.56×10^{-6}. It is important to understand the numbers in scientific notation, their order of magnitude and how to convert them into other units.

Quantities are written as a number between one and ten and then multiplied by an appropriate power of ten. Note that 'scientific notation', 'standard notation' and 'standard form' all have the same meaning.

SKILLBUILDER 1.2.1

Transforming decimal notation to scientific notation

Scientists use scientific notation to handle very large and very small numbers. For example, instead of writing 0.000000035, scientists would write 3.5×10^{-8}.

A number in scientific notation (also called standard form or power of ten notation) is written as:

$a \times 10^n$

where:

a is called the coefficient, and is a real number between 1 and 10, that is $1 \leq a < 10$

n is called the exponent, and is an integer (a positive or negative whole number); n is the power that 10 is raised to.

Note that if n is positive, then the number is larger than one, and if n is negative, then the number is less than 1.

To transform a very large or very small number into scientific notation, perform these steps.

1. Write the original number as a decimal number greater than or equal to 1 but less than 10.
2. Multiply the decimal number by the appropriate power of 10.

The exponent is determined by counting the number of places the decimal point needs to be moved to form the original number again.

- If the decimal point is moved n places to the right, n will be a positive number, for example $510 = 5.1 \times 10^2$.
- If the decimal point is moved n places to the left, n will be a negative number, for example $0.051 = 5.1 \times 10^{-2}$.

TABLE 1.2.1 Converting from scientific notation

Scientific notation	Number (expanded form)
1×10^{-9}	0.000000001
1×10^{-6}	0.000001
1×10^{-3}	0.001
1×10^{-1}	0.1
1	1
1×10^{1}	10
1×10^{3}	1000
1×10^{6}	1000000
1×10^{9}	1000000000

You will notice from Table 1.2.1 that when large numbers are written in scientific notation, the 10 has a positive exponential value. Very small numbers smaller than 1 are written with 10 to a negative exponent.

Test the skill

Convert 121 000 to scientific notation.

Examples of some values written in scientific notation are:

6.02×10^{23} particles

$25.25\,\text{mL} = 2.525 \times 10^{-2}\,\text{L}$

$0.00302\,\text{mol} = 3.02 \times 10^{-3}\,\text{mol}$

Values given in scientific notation show the significant numbers and indicate the precision of measurement during experimentation by the instrument. Precision and accuracy are covered in more detail in Module 1.5.

Worked example 1.2.1

CONVERTING TO SCIENTIFIC NOTATION

Write the following values in scientific notation.	
a The number of seconds in 1 day is 86 400.	
Thinking	**Working**
This number is larger than 1, so the exponent will be a positive value. There are 4 placeholders after the first digit, so 4 becomes the exponent.	86 400 has 8 as its first digit. There are 4 placeholders between the 8 and the final zero, so 4 is the exponent.
The coefficient is then 864 with a decimal point placed between the 8 and the 6.	Coefficient is 8.64
Write in scientific notation.	8.64×10^{4} seconds
b The Moon is moving away from Earth at a rate of 0.000 000 001 3 metres per second.	
Thinking	**Working**
This number is less than 1 so the exponent will be a negative number. There are 9 placeholders before the first non-zero digit, so the exponent is –9.	0.000 000 001 3 has 1 as its first non-zero digit. Including the zero in the units column, there are 9 zeros to the left of 1, so -9 is the exponent.
The coefficient is then 13 with a decimal point placed between the 1 and 3.	Coefficient is 1.3
Write in scientific notation.	1.3×10^{-9} metres per second

➤ Try yourself 1.2.1

CONVERTING TO SCIENTIFIC NOTATION

Write the following quantities in scientific notation.

a 4 000 000 m

b 0.000 000 000 000 000 000 1602 C

You should be routinely using scientific notation to express very large and very small numbers. This also involves learning to use your calculator intelligently. Scientific and graphics calculators can be put into a mode whereby all numbers are displayed in scientific notation. It is useful when doing calculations to use this mode rather than frequently attempting to convert to scientific notation by counting digits on the calculator display.

An important reason for using scientific notation is that it removes ambiguity about the precision of some measurements. For example, a measurement recorded as 240 g could be a measurement to the nearest gram; that is, somewhere between 239.5 g and 240.5 g, or it could have been rounded up to the nearest 10 g. By writing this quantity as 2.40×10^{2} g, it makes it clear the accuracy of the value (in this case, 3 **significant figures**).

Writing numbers using scientific notation

To write a number into long form from scientific notation, follow these rules.

- If the exponent is positive, write the coefficient without the decimal point. Continue to write zeros after the last digit in the coefficient so that the number of placeholders after the first digit is equal to the exponent.
- If the exponent is negative, write a zero in the units placeholder, then a decimal point. Continue to write zeros until the total number of zeros (including the zero in the units placeholder) is equal to the positive value of the exponent. Then write the coefficient without the decimal place.

Worked example 1.2.2

WRITING QUANTITIES FROM SCIENTIFIC NOTATION

Write the following values in long form.

a The mass of the neutron is 1.6749×10^{-27} kg.

b A light year is 9.4607×10^{15} m.

Thinking	Working
a The exponent is negative, which means the number in long form will be less than 1. Write a zero in the units column and then a decimal point. After the decimal point, write another 26 zeros followed by the coefficient without the decimal place.	0.000 000 000 000 000 000 000 000 001 6749 kg
b The exponent is positive, which means the number in long form is greater than 1. Write the coefficient, without the decimal point. There are 4 digits after the 9. So, write 11 more zeros to complete the number. 15 – 4 = 11	9 460 700 000 000 000 m

In both examples the number in long form has been written with three digits grouped together using thin spaces. Sometimes commas are used. This is purely for ease of reading and counting and is not compulsory.

➤ Try yourself 1.2.2

WRITING QUANTITIES FROM SCIENTIFIC NOTATION

Write the following values in long form.

a The force on an electron in a hydrogen atom is 8.2×10^{-8} N.

b The mass of the Moon is 7.342×10^{22} kg.

Scientific notation is the preferred way of communicating very large and very small measurements and information in physics. Often for convenience and ease of use, quantities in physics problems should first be converted into scientific notation before any calculations can be carried out.

ORDERS OF MAGNITUDE AND PREFIXES

As stated above, scientists often work with very large or very small numbers because of the measurements made during experimentation. Two methods are used to write down a physical measurement: prefixes and scientific notation.

The other form of communicating measured results is to use units that represent the order of magnitude. If 2.56×10^{-6} m was measured, it could be written either in the scientific notation as it is already, or as 256 µm. The symbol µ represents the prefix *micro* (Table 1.2.2), which means 'one millionth of the measured unit'. So, when *micro* is placed in front of metre, it becomes micrometre, meaning 'one millionth of a metre', therefore 256 µm becomes 256 millionths of a metre. Again, these are very small measurements and numbers. An SI **prefix** is a symbol written at the front of a unit to indicate that the measurement is a power of ten higher or lower than the unit itself.

There are 24 SI prefixes in use and most of them denote units that are one thousand (10^3) times larger or smaller than the previous prefix. Table 1.2.2 lists the SI prefixes commonly used in physics. You should become familiar with both scientific notation and prefixes for units of measurement. You should also be able to interchange them.

TABLE 1.2.2 The 24 official SI prefixes

Prefix	Symbol	Multiplier	Description	Decimal	Example
quetta	Q	10^{30}	quintillion	1 000 000 000 000 000 000 000 000 000 000	There is approximately 1400 quintillion litres of water on Earth
ronna	R	10^{27}	octillion	1 000 000 000 000 000 000 000 000 000	The human body contains approximately 10 octillion atoms
yotta	Y	10^{24}	septillion	1 000 000 000 000 000 000 000 000	The total power output of the Sun is 383 YW.
zetta	Z	10^{21}	sextillion	1 000 000 000 000 000 000 000	The diameter of the Milky Way galaxy is about 1 Zm.
exa	E	10^{18}	quintillion	1 000 000 000 000 000 000	1 EeV = 0.16 J
peta	P	10^{15}	quadrillion	1 000 000 000 000 000	1 light-year is approximately 10 Pm.
tera	T	10^{12}	trillion	1 000 000 000 000	1 TByte hard drives are now common
giga	G	10^{9}	billion	1 000 000 000	3.16 Gs = 1 century
mega	M	10^{6}	million	1 000 000	1 MHz is close to the frequencies at which TV stations broadcast.
kilo	k	10^{3}	thousand	1000	1 kg = 1000 grams
hecto	h	10^{2}	hundred	100	1 hPa is a unit used in meteorology to describe atmospheric pressure.
deca	da	10^{1}	ten	10	1 daN is approximately the force exerted by a 1 kg object on the surface of Earth.
–	–	1	unit	1	–
deci	d	10^{-1}	tenth	0.1	1 L = 1 dm^3
centi	c	10^{-2}	hundredth	0.01	1 cg of water takes up 1 mL of space.
milli	m	10^{-3}	thousandth	0.001	There are 1000 mm in 1 m.
micro	μ	10^{-6}	millionth	0.000 001	μg are commonly used as the unit for medicine dosage.
nano	n	10^{-9}	billionth	0.000 000 001	The wavelength of yellow sodium streetlights is 550 nm.
pico	p	10^{-12}	trillionth	0.000 000 000 001	The diameter of the hydrogen atom is about 100 pm.
femto	f	10^{-15}	quadrillionth	0.000 000 000 000 001	Some lasers emit a pulse of light that lasts for 1 fs.
atto	a	10^{-18}	quintillionth	0.000 000 000 000 000 001	Quarks and electrons are believed to be 1 am in size.
zepto	z	10^{-21}	sextillionth	0.000 000 000 000 000 000 001	160 zJ is approximately 1 eV.
yocto	y	10^{-24}	septillionth	0.000 000 000 000 000 000 000 001	The mass of a proton is approximately 1.7 yg.
ronto	r	10^{-27}	octillionth	0.000 000 000 000 000 000 000 000 001	The atomic mass unit (amu) is 1.66×10^{-27} kg
quecto	q	10^{-30}	quintillionth	0.000 000 000 000 000 000 000 000 000 001	The mass of an electron is approximately 1 quintillionth of a kilogram

SI prefixes are used to avoid writing very small or very large numbers with lots of zeros. The prefix is added directly to the name of a unit, and a prefix symbol attaches directly to the symbol for a unit.

The larger prefixes are written as a capital letter, while the smaller prefixes are written using a lowercase letter. It is important to give a symbol the correct case (upper or lower). There is a big difference between 1 mm and 1 Mm.

Note that the fundamental unit kilogram has itself a prefix, but all multiples of mass are written with the base unit grams. As an example, one million kilograms is not written as one megakilogram, but as one gigagram (Gg). Do not put spaces between the prefixes and the unit symbols.

Before any measurements with a prefix can be substituted into a formula, they must be converted into SI units without the prefix, i.e. in scientific notation.

SKILLBUILDER 1.2.2

Converting into SI units

Often in science you may need to convert from one unit to another to complete a calculation. Knowing how to change between units is an important skill; however, conversion factors should be used carefully. As some units of measurement are difficult to visualise, knowing the size of different units in relation to each other will aid your understanding and help you avoid errors in your calculations. The most common mistake made with conversion factors is multiplying rather than dividing.

Usually, these conversions are straightforward, such as the conversion between kilometres and meters shown in Worked example 1.2.3 where only the prefix needs to be considered. More detailed conversions will be looked at in module 1.4.

Worked example 1.2.3

CONVERTING INTO SI UNITS

Convert 60 700 grams to kilograms.

Thinking	Working
Consider the unit conversion from grams to kilograms. Since 1 kg = 1000 g, the kg is replaced by 1 and the g is replaced by 1000.	$= g \times \frac{kg}{g}$ $= \cancel{g} \times \frac{kg}{\cancel{g}}$ $= kg$
To convert grams to kilograms, multiply by kg per g.	$= \frac{60\,700}{1} \times \frac{kg}{g}$ $= \frac{60\,700}{1} \times \frac{1}{1000}$ $= 60.7\ kg$

➤ Try yourself 1.2.3

CONVERTING BETWEEN UNITS

Determine how many am are in 5.91 Ym.

When converting from one unit to another it is essential that you check that the answer makes sense. For instance, if converting from µm to km, you would expect that there are many µm in a km. The inversion of prefix conversions is one of the major sources of mistakes in general physics.

1.2 Review

SUMMARY

- 'Scientific notation', 'standard notation' and 'standard form' all have the same meaning.
- A number in scientific notation is written as $a \times 10^n$, where:
  - a is called the coefficient, and is a real number between 1 and 10, that is, $1 \leq a < 10$
  - n is called the exponent and is an integer (positive or negative).
- A range of scientific symbols is used to represent 10^n.
- The SI prefixes are symbols that go before a unit and indicate multiplication of a power of 10 of the unit.

KEY QUESTIONS

Describe

1 State why physicists need to write numbers in scientific notation instead of long form.

2 Identify the two numbers between which the coefficient of a number expressed in scientific notation has to lie.

3 State what the unit Tg means.

Apply

4 Represent the following values in scientific notation.
- **a** 637 nm
- **b** 319 s

5 Represent the following numbers in long form.
- **a** 1.1×10^{-10} m
- **b** 7.031×10^{6} m s^{-2}

6 Determine the order of magnitude of the following values.
- **a** 6.41×10^{9} m
- **b** 1.201×10^{-3} m^3

7 Match each number with its scientific notation.

Number	Scientific notation
0.002	2×10^{3}
2000	1.234×10^{-1}
0.1234	2×10^{-3}
123.4	1.234×10^{1}
12.34	1.234×10^{2}

Analyse

8 Convert the following lengths into the unit in brackets, presenting the information in scientific notation.
- **a** 1.56 mm (μm)
- **b** 8.35 nm (cm)

9 A human hair is about 50 μm wide, whereas a virus is 2×10^{-8} m wide. How many times wider than the width of the virus is the width of the human hair?

10 Determine which is the bigger difference in order of magnitude:
- **a** the mass of a human being to the mass of the nucleus of a carbon atom (mass = 1.99×10^{-26} kg)
- **b** the mass of the universe (estimated to be about 5×10^{52} kg) to the mass of a human being

1.3 Mathematical basics for physics

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that the rules of mathematics apply for solving mathematical operations or calculations in physics
- perform basic mathematical operations using percentages and fractions
- rearrange and substitute formulas using algebraic rules
- use the trigonometric ratios to determine side lengths and angles of right-angled triangles
- use the equation of a straight line to determine its gradient and *y*-intercept.

Mathematics is often described as the language of physics. The theories, models, laws and principles used in physics all have their basis in mathematics. Physics extensively uses all aspects of mathematics, from the simplest application of percentage to the addition of three-dimensional magnetic field vectors. To do well in physics you must have knowledge of the following branches of mathematics.

Note that all physics formulas are written using algebraic representation. This means that the variables used in any formula are given symbols and their relationship to each other is linked by a set of mathematical operations that include addition, subtraction, multiplication, division, powers and roots.

When conducting mathematical operations or calculations, remember all the rules of mathematics apply, including:

- order of operations
- rules for transposing formulas and working with fractions
- substitutions
- approximations.

PERCENTAGES

Percentages are used when calculating relative amounts of measurements, such as uncertainties and efficiencies.

To calculate a percentage, $P\%$, of an amount, x:

$$x \times \frac{P\%}{100}$$

To express x out of y as a percentage, $P\%$:

$$P\% = \frac{x}{y} \times 100$$

PROBABILITY

In physics, probability is used in thermal, quantum and atomic physics. It is defined as the chance that an event, E, can occur:

$$P(E) = \frac{\text{number of times } E \text{ can occur}}{\text{total number of possible events}}$$

FRACTIONS

Fractions are used extensively throughout physics in such areas as electricity, optics and waves.

When adding or subtracting fractions, the denominators must be equal.

When multiplying fractions, multiply the numerators and write that as a fraction over the denominators multiplied together:

$$\frac{a}{b} \times \frac{c}{d} = \frac{ac}{bd}$$

When dividing fractions, write the divisor (the fraction to be divided) as its reciprocal (i.e. upside-down) and then multiply the fractions together:

$$\frac{a}{b} \div \frac{c}{d} = \frac{a}{b} \times \frac{d}{c} = \frac{ad}{bc}$$

Or, if a whole number, a, is divided by a fraction:

$$a \div \frac{c}{d} = a \times \frac{d}{c} = \frac{ad}{c}$$

INDICES AND LOGARITHMS

Index laws

Indices, or powers, are also used extensively in physics in scientific notation (e.g. $3 \times 10^8\,\text{m s}^{-1}$) as well as in many formulas (e.g. $\Delta E = \Delta mc^2$). The following rules for working with indices may be helpful.

$$a^x \times a^y = a^{x+y}$$

$$a^x \div a^y = \frac{a^x}{a^y} = a^{x-y}$$

$$\left(a^x\right)^y = a^{xy}$$

$$a^0 = 1$$

$$a^1 = a$$

$$a^{-1} = \frac{1}{a}$$

$$a^{-x} = \frac{1}{a^x}$$

$$a^{\frac{1}{2}} = \sqrt{a}$$

$$a^{\frac{1}{x}} = \sqrt[x]{a}$$

Logarithms

Logarithms are a useful mathematical operation that can be used to find the value of indices. For example, they can be used with decay equations such as $N = N_0\left(\frac{1}{2}\right)^n$

A detailed analysis of logarithms is beyond the scope of this course. However, logarithms to base 10 (written as just 'log') can be used quite easily to simplify decay equations, instead of using a best-guess method.

The following general rules for working with logs may be helpful.

$$\log xy = \log x + \log y$$

$$\log \frac{x}{y} = \log x - \log y$$

$$\log x^y = y \log x$$

These rules can be used to determine the value of n in the decay equation. Logs are taken of both sides:

$$N = N_0\left(\frac{1}{2}\right)^n$$

$$\log N = \log\left(N_0\left(\frac{1}{2}\right)^n\right)$$

$$\log N = \log N_0 + \log\left(\frac{1}{2}\right)^n$$

$$\log N = \log N_0 + n\log\left(\frac{1}{2}\right)$$

$$n = \frac{\log N - \log N_0}{\log\left(\frac{1}{2}\right)}$$

This can then be solved using the log function on your calculator.

ALGEBRA

Algebra is a powerful tool in solving physics problems. Measurements and data often need to be substituted into a formula in order to obtain an answer. Remember that the data that is to be substituted should always be written without a prefix but in an SI unit, and preferably in scientific notation.

If an unknown variable in a formula needs to be evaluated, then two strategies can be employed:

- The formulas can be rearranged to make the unknown variable the subject of the equation, and then the values substituted in.
- Alternatively, the values can be substituted into the formula and then the formula can be rearranged to make the unknown variable the subject.

Worked example 1.3.1

USING ALGEBRA IN FORMULAS

The kinetic energy (E_k) of a 0.224 kg toy car, m, moving at an unknown speed, v, is 1.61×10^{-3} J.

Kinetic energy is given by the formula:

$$E_k = \frac{mv^2}{2}$$

Calculate the velocity of the car by first substituting in the known values, and then rearranging the formula.

Thinking	Working
Substitute in the known values.	$E_k = \frac{mv^2}{2}$ $1.61 \times 10^{-3} = \frac{0.224 \times v^2}{2}$
Rearrange the equation so that v is the subject.	$1.61 \times 10^{-3}\ 2 = 0.224 \times v^2$ $v^2 = \frac{1.61 \times 10^{-3} \times 2}{0.224}$ $v = \sqrt{\frac{1.61 \times 10^{-3} \times 2}{0.224}}$
Then solve the equation for v.	$v = \sqrt{\frac{3.22 \times 10^{-3}}{0.224}}$ $= \sqrt{0.014375}$ $= 0.12\ \text{m s}^{-1}$
State the answer using the correct units.	The toy car's velocity is $0.12\ \text{m s}^{-1}$.

➤ Try yourself 1.3.1

USING ALGEBRA IN FORMULAS

The formula relating how much energy per second, P, is released by the Sun is:

$$P = \sigma A T^4$$

where

P is the energy released by the Sun per second in watts

σ is the Stefan–Boltzmann constant 5.67×10^{-8}.

A is the surface area of the Sun in m^2

T is the surface temperature of the Sun in kelvin

If the surface area of the Sun is $6.1 \times 10^{18} m^2$, and it produces 3.8×10^{26} watts, determine its surface temperature by first rearranging the formula, then substituting known values.

Quadratic formula

The quadratic formula is sometimes used in more difficult physics problems in which a question can have one, two or no solutions. It is used when the unknown variable is written in an equation with a power of one as well as a power of two. Examples of these questions occur in motion, gravity, electric fields and in electricity.

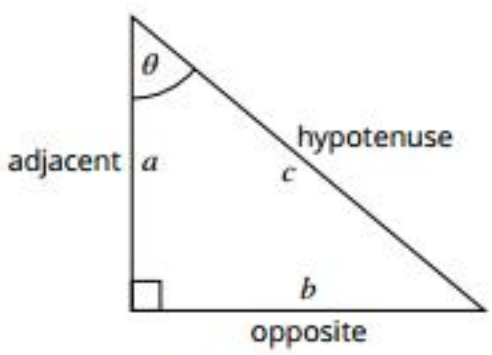
$$\text{If } ax^2 + bx + c = 0, \text{ then } x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

GEOMETRY

Understanding the direction and shape of many abstract ideas in physics requires knowledge of the basics of angles, area, perimeter, volume and trigonometry. These concepts occur throughout every aspect of physics, especially where direction is important.

Pythagoras' theorem

Right-angled triangles are used extensively when vectors are being added or subtracted. Pythagoras' theorem can be used to find unknown side lengths in any right-angled triangle, as shown in Figure 1.3.1.



$$c^2 = a^2 + b^2$$

FIGURE 1.3.1 Pythagoras' theorem is used for right-angled triangles.

Trigonometry

The sine, cosine and tangent ratios are also used to determine the sizes and directions of vector quantities in physics. Using the triangle in Figure 1.3.1 the trigonometry ratios can be calculated as follows:

$$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}} \qquad \cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}} \qquad \tan\theta = \frac{\text{opposite}}{\text{adjacent}}$$

MEASUREMENT

Many concepts in physics require the use and calculation of perimeters, areas, surface areas and volumes. Complex objects are often approximated by circles and spheres.

Circumference, C, of a circle with radius r.

$$C = 2\pi r$$

Area, A, of a circle with radius r.

$$A = \pi r^2$$

Surface area, SA, of a sphere with radius r.

$$SA = 4\pi r^2$$

Volume, V, of a sphere with radius r.

$$V = \frac{4\pi r^3}{3}$$

Volume, V, of a cylinder with height h and base radius r.

$$V = \pi r^2 h$$

STRAIGHT LINE GRAPHS

A straight line is the simplest relationship between two variables. In graphical analysis of physics phenomena, a straight line is useful, as the y-intercept and gradient can be calculated. Figure 1.3.2 shows a typical straight-line relationship.

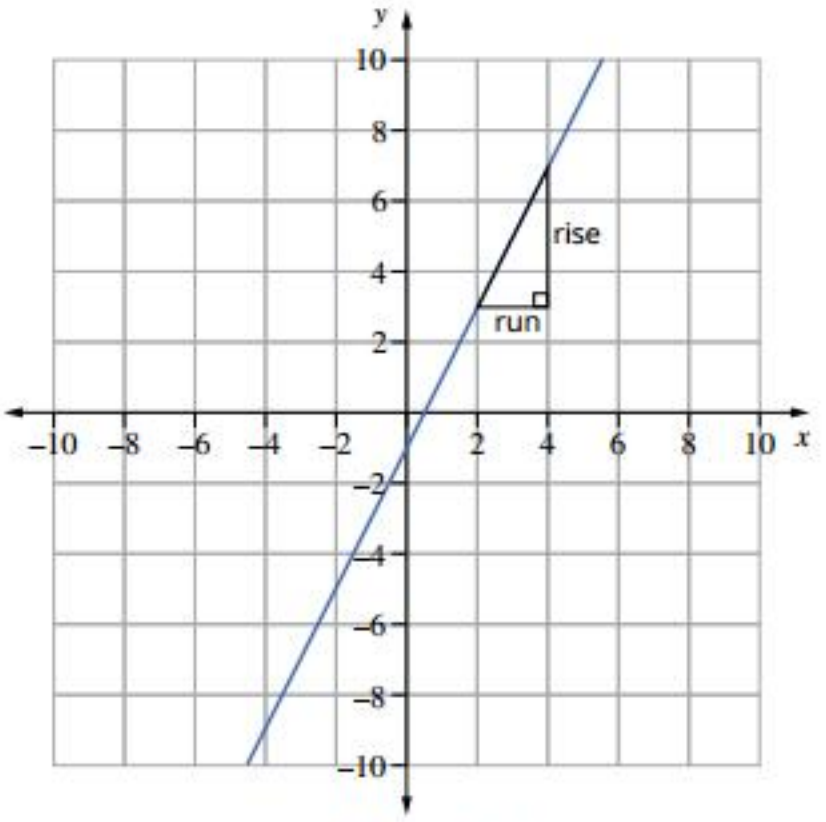


FIGURE 1.3.2 A graph representing a simple relationship between two variables

The gradient of any straight line is calculated using:

$$\text{gradient, } m = \frac{\text{rise}}{\text{run}} = \frac{\Delta y}{\Delta x}$$

The y-intercept, c, is read off the y-axis.

The equation of any straight line is determined by the gradient and y-intercept:

$$y = mx + c$$

In the example in Figure 1.3.2, the equation of the straight line is $y = 2x - 1$ with a gradient of 2 and y-intercept of -1.

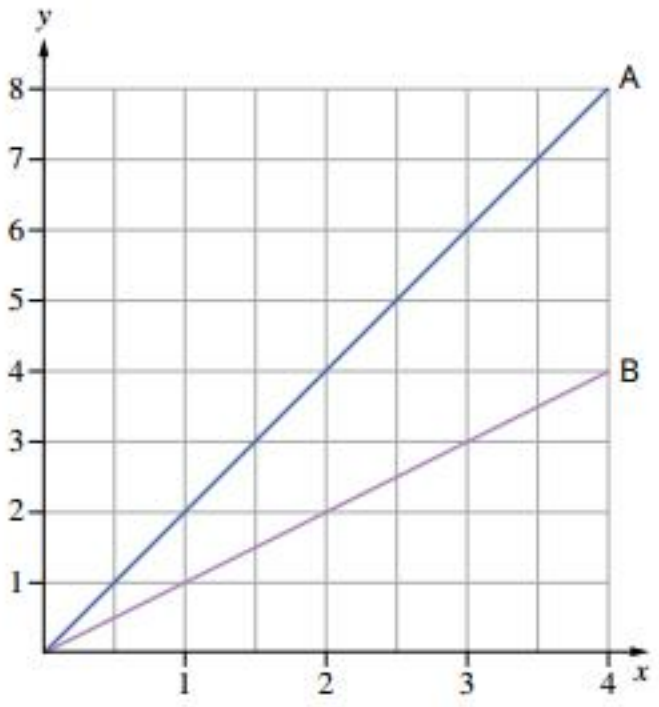
SKILLBUILDER 1.3.1

Interpreting the slope of a linear graph

Scientists often represent a relationship between two variables as a graph. For directly proportional relationships, the variables are related to each other by a straight line, where the slope (or gradient) of the line represents the constant of proportionality between the two variables.

The slope or gradient of the line is defined as the ratio of change between two points in the vertical axis (Δy), divided by the change between two points in the horizontal axis (Δx). In other words, it measures the rate at which one variable (the dependent variable) changes with respect to the other (the independent variable).

The graph shown has two straight lines with different slopes. The steeper slope (blue line, A) indicates that the rate of change is higher. This means the change is happening more quickly. On the other hand, the flatter slope (lilac line) indicates that the rate of change is lower. This means the change is happening more slowly.



More information about interpreting the relationship between two variables is in Module 1.6.

Worked example 1.3.2

INTERPRETING THE SLOPE OF A LINEAR GRAPH

On a graph with two sloped lines, identify what the steeper sloped line indicates.

A a faster rate of change
B a slower rate of change
C the same rate of change
D a much slower rate of change

Thinking	Working
The slope or gradient of the line is defined as the ratio of change between two points in the vertical axis (Δy), divided by the change between two points in the horizontal axis (Δx).	**A** is correct. The steepness of the slope indicates the rate of change. A line with a steeper slope indicates a faster rate of change.

➤ Try yourself 1.3.2

INTERPRETING THE SLOPE OF A LINEAR GRAPH

Identify which of the following options indicates the rate of change of a straight line on a graph.

A area under the graph
B *y*-intercept
C *x*-intercept
D gradient

1.3 Review

SUMMARY

- When conducting mathematical operations or calculations, remember all the rules of mathematics apply, including:
  - order of operations
  - rules for transposing formulas and working with fractions
  - substitutions
  - approximations.
- Percentages and fractions are basic mathematical skills that are applicable in all fields of physics.
- Performing substitution and rearranging of physics formulas is vital to solving numerical calculations.
- The trigonometric ratios of sine, cosine and tangent are used to determine directions of many physical quantities.
- Complex shapes can be approximated using circles, spheres and cylinders, and then calculating their area, surface area and volume using the appropriate formula.
- The analysis of a straight line is very important in physics as the gradient and *y*-intercept often contain useful information about physical relationships.

KEY QUESTIONS

Describe

1 State the formula for calculating the gradient of a straight line.

2 Write the three trigonometric ratios in terms of the sides of a right-angled triangle.

Apply

3 Determine the gradient (m) and y-intercept of the following straight lines.

a $y = x - 7$

b $2y = 16 - 4x$

c $4.5y + 2.1x - 7 = 0$

4 Rearrange the following formulas so that the variable in brackets is the subject of the equation.

a $F = ma$ (a)

b $E_k = hf - \phi$ (f)

c $F = \dfrac{GMm}{r^2}$ (r)

Analyse

5 A student recorded the following temperatures of water.

Time (min)	Temperature (°C)
0	22
2	34
4	43
5	50
8	64
10	78

a Calculate the average temperature change per minute during the experiment.

b Determine whether the increase was constant throughout the experiment.

6 WASP-17b is an exoplanet discovered in 2009 that has a radius twice that of Jupiter. Determine how many times the volume of Jupiter this is. The relationship between the radius, r, and volume, V, of a sphere is given by the formula $V = \dfrac{4\pi r^3}{3}$.

7 Solve the following problems.

a $\dfrac{1}{2} + \dfrac{1}{8}$

b $10 \div \dfrac{4}{5}$

c 15% of 76.2 kg

8 Simplify each of the following.

a $\dfrac{t^3 \times t}{\sqrt{t}}$

b $c\left(\dfrac{c^2}{c}\right)^3$

9 Substitute the following values into the formula below to obtain a value and units for γ:

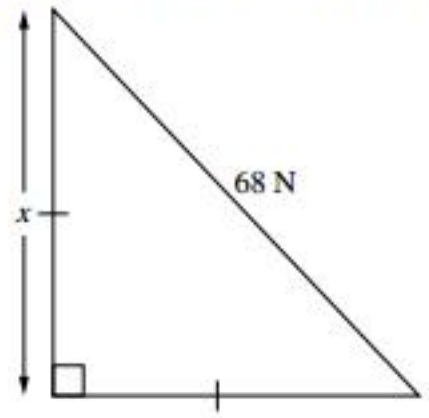
$c = 3.00 \times 10^8 \text{ m s}^{-1}$

$v = 2.99 \times 10^8 \text{ m s}^{-1}$

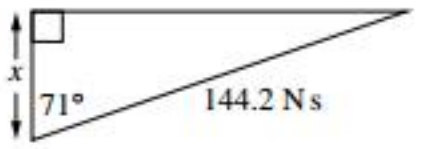
$\gamma = \dfrac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}}$

10 Determine the value of x in the following triangles:

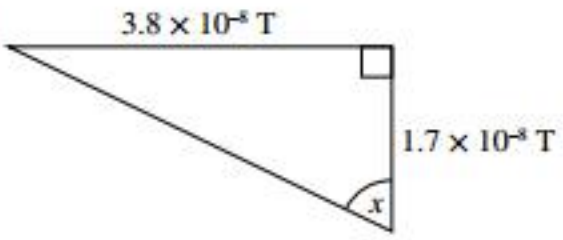
a



b



c

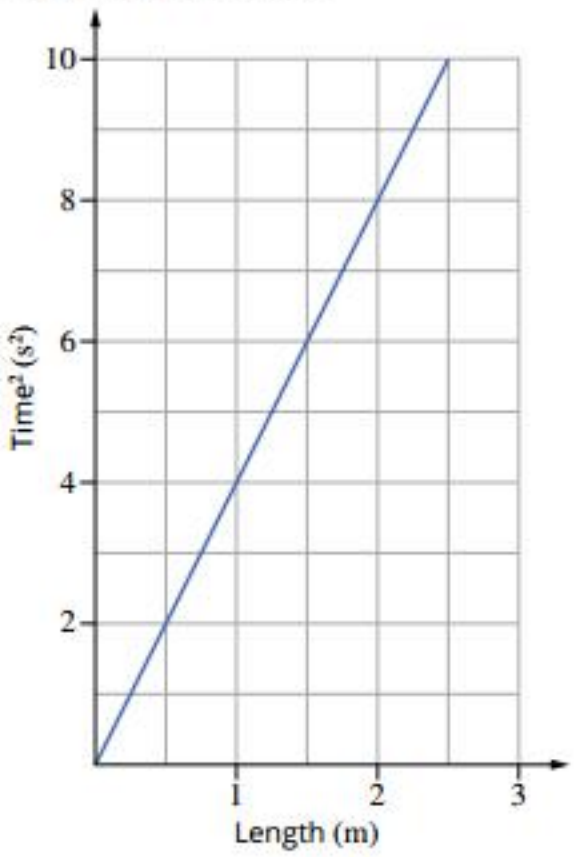


11 Solve the following equation for a positive value of x.

$$\frac{kq^2}{x^2} = \frac{4kq^2}{(1-x)^2}$$

where k and q are constants.

12 The graph below shows how the time for one complete swing of a pendulum, squared, changes with the length of a pendulum.



a Determine the gradient and y-intercept of the line.

b Identify the units of the gradient and y-intercept.

c If the gradient of the line is theoretically equal to $\frac{4\pi^2}{g}$, determine the value, and units, of g.

13 *Rearrange* $N = N_0\left(\frac{1}{2}\right)^n$ to make n the subject.

14 Solve for n in the following equations:

a $0.25 = 2\left(\frac{1}{2}\right)^n$

b $20 = 450\left(\frac{1}{2}\right)^n$

1.4 Units

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- appreciate that physics uses the International System (SI) of units
- recall fundamental units, their symbols and definitions
- convert between various units of the same type using SI and some non-SI units.

Science uses a specific system of units to describe measurements that are made. In physics, measurements are made using the **International System (SI)** of units. Most countries around the world use and understand these units as they are internationally accepted in science, commerce, sport and everyday life.

MEASUREMENT AND UNITS

Every science needs a system of units to describe the measurements that are made. In physics, measurements are made using the International System (SI) of units. Make sure the units you measure or observe are accurate and remember to use SI units when recording your evidence. Table 1.4.1 presents common quantities and SI units used in physics.

TABLE 1.4.1 The seven fundamental SI units used in physics, along with their symbols

Quantity	SI unit	Symbol for SI unit
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Correct use of unit symbols

The correct use of unit symbols removes ambiguity, as symbols are recognised internationally. Some important points to keep in mind when writing units and recording measurements and numbers are given in Table 1.4.2.

Uppercase letters are only used for the *symbols* of the units that are named after people. For example, the unit of energy is joule and the symbol is J. The joule was named after James Joule who was famous for studies into energy conversions. The exception to this rule is 'L' for litre. Uppercase 'L' is used because a lowercase 'l' looks like the numeral '1'.

The product of several units is shown by separating the symbol for each unit with a space. The division or ratio of two or more units can be shown in fraction form, using a slash, or using negative indices. Prefixes should not be separated by a space.

TABLE 1.4.2 Examples of correct and incorrect use of symbols for derived units

Rule	✓	✗
Numbers and symbols should not be mixed.	thirty grams 30 g	thirty g 30 grams
Do not put spaces between prefixes and unit symbols.	kg mL kPa	k g m L k Pa
Write the correct case for symbols (upper- or lower-case).	1 mm 84 kg 5.2 mL	1 Mm 84 KG 5.2 mL
SI units should not be followed by a full stop unless they are at the end of a sentence. The symbols for units are not abbreviations.		
Only use upper-case letters for unit symbols named after people. The exception is 'L' for litre, to avoid confusion because 'l' looks like the numeral '1'.	J	
Units named after people can take the plural form by adding an 's' when used with numbers greater than one. Never do this with the unit symbols.	two kilojoules	2 kJs
The product of a number of units is shown by separating the symbol for each unit with a space.	0.1 mol dm^{-3}	0.1 moldm^{-3}
The division or ratio of two or more units can be shown in fraction form, using a slash, or using negative indices. A space is always used between different units. For example, closing up metres and seconds as ms suggests that m is a prefix (milli) rather than a unit (metres).	9.8 m/s 9.8 ms^{-1} $Jg^{-1}°C^{-1}$	9.8 m/s^{-1}

When units are displayed with a negative exponent, such as ms^{-1}, the negative value of the exponent signifies the division of the units; in other words, per unit. In this case, ms^{-1} is the same as m/s, or metres per second.

DERIVED UNITS

Every other unit that is used in physics is a mathematical combination (such as division, multiplication, squaring) of one or more of the seven fundamental units, and are called derived units. Table 1.4.3 lists some of the most common units encountered in high school physics.

TABLE 1.4.3 Some of the most common derived units in high school physics

Quantity and symbol	SI unit	Symbol for SI unit	Notes
area, A	square metre	m^2	
volume, V	cubic metre	m^3	
amount of liquid, V	litre	L or l	$1\,L = 1000\,cm^3 = 0.001\,m^3$
density, $\tilde{n}$	kilograms per cubic metre	$kg\,m^{-3}$	
velocity, v	metres per second	$m\,s^{-1}$	
acceleration, a	metres per second squared	$m\,s^{-2}$	
current, I	ampere	A	
momentum, p	kilogram metres per second	$kg\,m\,s^{-1}$	$1\,kg\,m\,s^{-1} = 1\,N\,s$
force, F	newton	N	$1\,N = 1\,kg\,m\,s^{-2}$
energy, E	joule	J	$1\,J = 1\,N\,m$
power, P	watt	W	$1\,W = 1\,J\,s^{-1}$
charge, q	coulomb	C	$1\,C = 1\,A\,s$
frequency, f	hertz	Hz	$1\,Hz = 1\,s^{-1}$
pressure, P	pascal	Pa	$1\,Pa = 1\,N\,m^{-2}$
voltage, V	volt	V	$1\,V = 1\,J\,C^{-1}$
resistance, R	ohm	Ω	$1\,\Omega = 1\,V\,A^{-1}$
magnetic flux density, B	tesla	T	$1\,T = 1\,N\,A^{-1}\,m^{-1}$
magnetic flux, Φ	weber	Wb	$1\,Wb = 1\,T\,m^2$
activity, A	becquerel	Bq	$1\,Bq = 1$ decay s^{-1}

i A derived unit is a unit that is a mathematical combination of one or more of the seven fundamental units.

NON-SI UNITS USED IN PHYSICS

Two non-SI units are used extensively in physics, the kWh and the eV, and they are both units of energy.

The kilowatt-hour, kWh, is used to describe the amount of energy used or supplied to homes by power stations. Note that this unit is **not** kilowatts *per* hour but kilowatts times hour.

$$1\,kWh = 3.60 \times 10^6\,J$$

The electron volt, eV, is used to describe the energies of subatomic particles.

$$1\,eV = 1.602 \times 10^{-19}\,J$$

UNIT CONVERSIONS

When derived units are used, conversion factors are required (such as 1 minute = 60 seconds). For example, values of energy can be converted between electron volts (eV) and joules (J) using $1\,\text{eV} = 1.602 \times 10^{-19}\,\text{J}$

Care should be taken when unit conversions involve non-SI units and rates. One example is the conversion between kilometres per hour and meters per second. In this case the kilometres would need to be converted to meters and the hours would need to be converted to seconds:

$100\,\text{km} = 1\,000\,000\,\text{m}$

1 hour = 60 minutes = 3600 seconds

$$\text{So, } 100\,\text{km h}^{-1} = \frac{100\,\text{km}}{1\,\text{h}} = \frac{1\,000\,000\,\text{m}}{3600\,\text{s}} = 27.8\,\text{m s}^{-1}$$

This conversion will be explored in more detail in Chapter 6. A similar example is the conversion between units for volume and capacity in Worked example 1.4.1.

Worked example 1.4.1

UNIT CONVERSIONS

Calculate how many litres are in one cubic kilometre.	
Thinking	**Working**
Write each unit in terms of m^3. Remember that a km^3 is a cube that has sides of 1000 m by 1000 m by 1000 m.	$1\,\text{L} = 0.001\,\text{m}^3$ and $1\,\text{km}^3 = 1000\,\text{m} \times 1000\,\text{m} \times 1000\,\text{m} = 10^9\,\text{m}^3$
Take the inverse of each equation to find the equivalent volume in m^3.	$1\,\text{m}^3 = \frac{1}{10^9} = 10^{-9}\,\text{km}^3$ and $1\,\text{m}^3 = \frac{1}{0.001} = 10^3\,\text{L}$
Now equate them since they are both equal to $1\,\text{m}^3$.	$10^{-9}\,\text{km}^3 = 10^3\,\text{L}$ $\therefore \frac{10^3\,\text{L}}{10^{-9}\,\text{km}^3} = 10^{12}\,\text{L km}^{-3}$
State the answer.	There are 10^{12} or one trillion litres in 1 cubic kilometre.

➤ Try yourself 1.4.1

UNIT CONVERSIONS

If a person weighs $6.0 \times 10^1\,\text{kg}$ and the mass of a single carbon atom is $1.99 \times 10^{-23}\,\text{g}$, calculate how many carbon atoms would be needed to equal the mass of the person.

1.4 Review

SUMMARY

- Physics uses the International System (SI) of units.
- There are seven fundamental units: metre, second, kilogram, kelvin, mole, ampere and candela.
- Units with a prefix need to be converted into scientific notation before they can be used in a physics formula.
- When converting units, it is very useful to write the conversions as fractions and then cross-cancel out to ensure that the conversion is done correctly.
- When units are displayed with a negative exponent, the negative value of the exponent signifies the division of the units. For example, g mL^{-1} is the same as g/mL or grams per millilitre.
- When writing and recording measurements, remember:
  - numbers and symbols should not be mixed
  - do not put spaces between prefixes and unit symbols
  - write the correct case for symbols (upper or lower).

KEY QUESTIONS

Describe

1 State the standard unit of measurement, and the symbol, for the following quantities.
- **a** time
- **b** temperature
- **c** length
- **d** mass

2 List the following units from largest to smallest: centi, milli, deci, mega, kilo, nano, micro.

Apply

3 Explain why it is important that general society, not just the scientific community, needs a systematic and consistent set of units for measurement.

4 Explain the difference between fundamental units and derived units.

Analyse

5 Convert 30.00 mL into L.

6 Identify any errors in the recordings below and correct them.
- **a** 23 mL/g h^{-1}
- **b** 79 kI s^{-1}
- **c** four litres
- **d** 1.56 grams

7 Determine how many metres there are in the 656 nanometres wavelength of red light emitted from hydrogen.

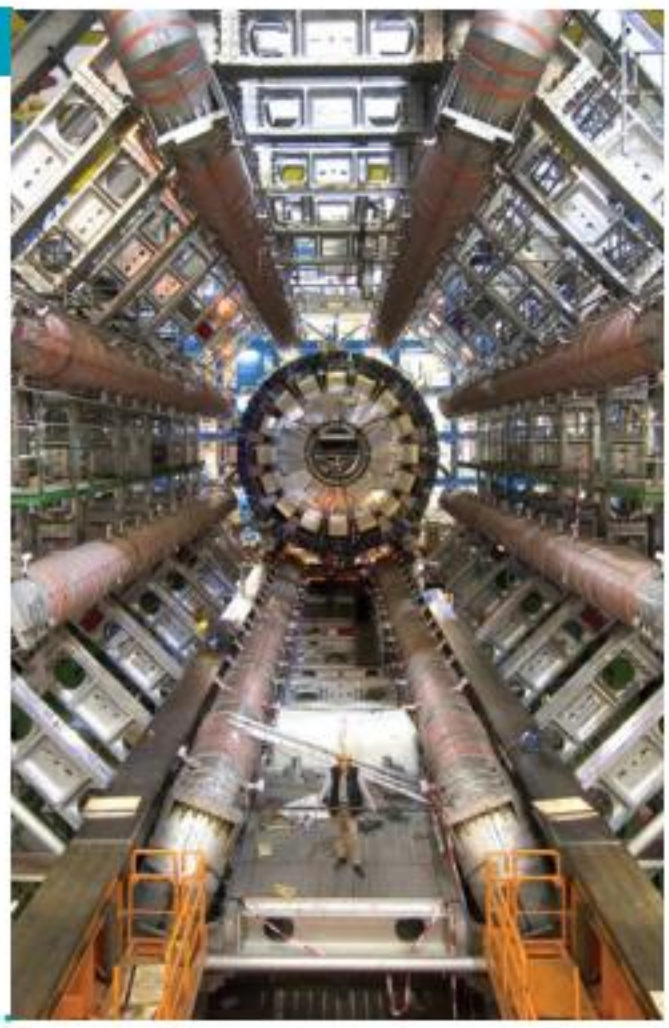
8 Show that the unit ohm can be written in fundamental units as:

$$1\,\Omega = 1\left(\frac{kg\,m^2}{A^2\,s^3}\right)$$

1.5 Measuring precision and accuracy using uncertainties and percentage error

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- explain the difference between accuracy and precision
- explain the difference between uncertainty and error
- calculate uncertainty and error values for measurements
- write measurements with uncertainty and error values
- write measurements and calculations to the correct number of significant figures
- perform calculations that contain uncertainty or error values
- understand that all measurements made in physics experiments are subject to a level of uncertainty
- differentiate between accuracy and precision, and know how to express these quantitatively using significant figures
- perform calculations using significant figures
- explain the difference between mistakes, systematic uncertainties and random uncertainties
- determine the absolute uncertainty of a value based on the precision of the instrument
- convert between absolute and percentage uncertainties
- calculate a value along with the associated uncertainty.



All measurements are limited by the instrument used and the observer. Accuracy of the measurements and results are therefore affected. Instruments have a prescribed level of precision and cannot measure within the smallest increment of the device. In addition, a scientist's technique and experience with the instrument influences the precision with which the reading can be made.

However, in science it is impossible to measure the true value, as there will always be some degree of **uncertainty**. This results in **error** and uncertainty in the values measured or observed. Therefore, science can be thought of as developing evidence-based results that have some limitations. Measurements with uncertainty and errors are normal in science and so results are always presented with a **range** (e.g. ±0.5) indicating possible precision, or processed through statistical calculations.

ACCURACY AND PRECISION

In science and statistics, the terms *accuracy* and *precision* have very specific and different meanings.

- **Accuracy** is the ability to obtain the correct measurement. To obtain accurate results, you must minimise **systematic errors**.
- **Precision** is the ability to consistently obtain the same measurement. To obtain precise results, you must minimise **random errors**.

The percentage error (or measurement error written as a percentage) in the measurement is the difference between the measurement and the accepted value, written as a percentage:

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{accepted value}}{\text{accepted valued}}\right| \times 100\%$$

As an example, the speed of light is $299\,792\,453\,\text{m}\,\text{s}^{-1}$.

The accuracy of a measurement is how close it is to an accepted value.

i The precision of a measurement is how many digits can be written down to describe the measurement.

An accurate measurement for the speed of light is $300\,000\,000\,\text{m s}^{-1}$, which has only a 0.07% percentage error:

$$\left|\frac{300\,000\,000 - 299\,792\,453}{299\,792\,453}\right| \times 100\% = 0.07\%$$

An inaccurate measurement for the speed of light is $780\,000\,000\,\text{m s}^{-1}$, which has a 160% percentage error:

$$\left|\frac{780\,000\,000 - 299\,792\,453}{299\,792\,453}\right| \times 100\% = 160\%$$

Devices that use smaller and smaller units to measure in are also said to be precise. Common examples are Vernier callipers and micrometers.

To understand more clearly the difference between accuracy and precision, think about firing arrows at an archery target (Figure 1.5.1 on page e34). Accuracy is being able to hit the bullseye, whereas precision is being able to hit the same spot every time you shoot.

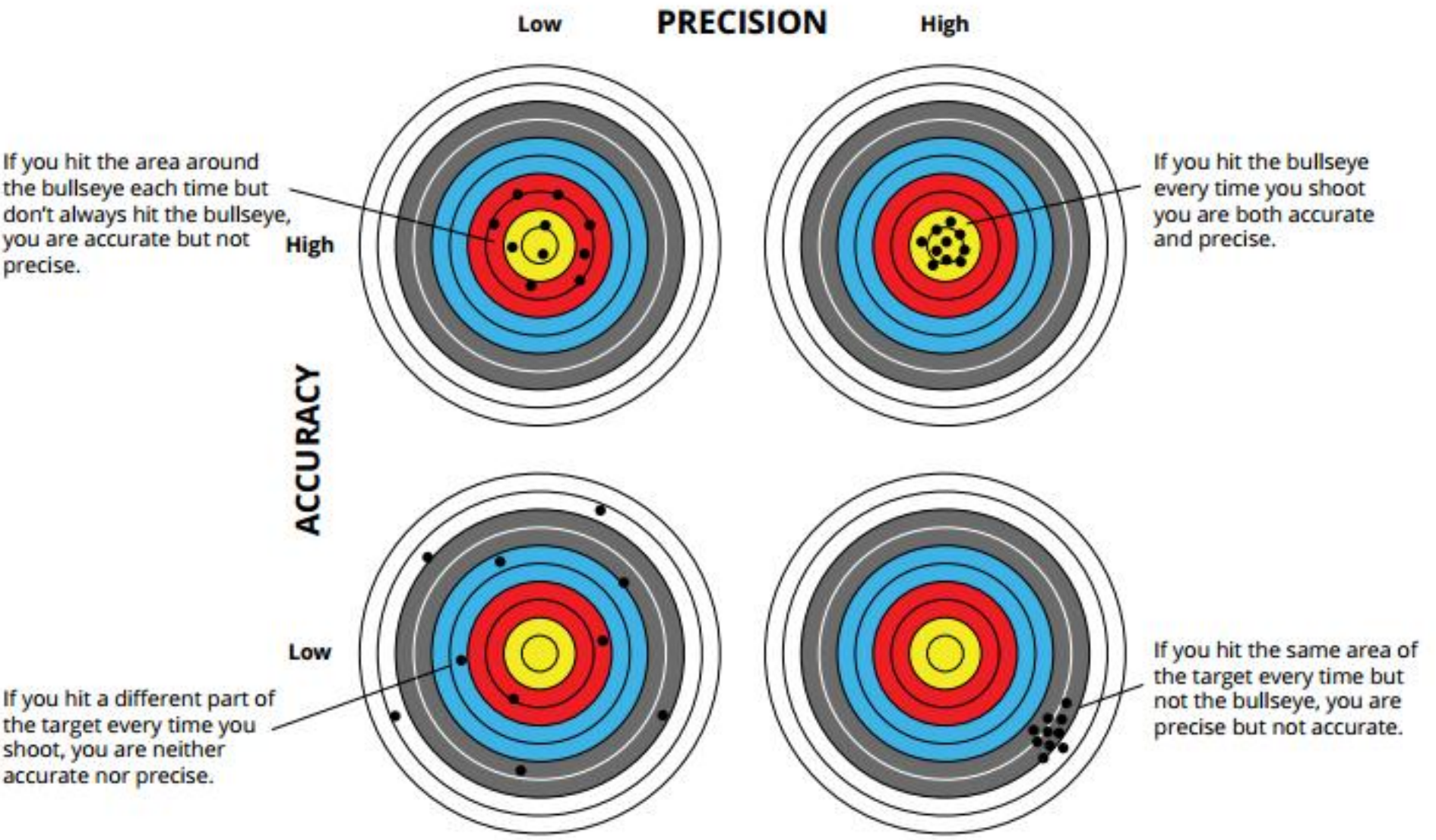

PRECISION
Low
High
ACCURACY
High
Low
If you hit the area around the bullseye each time but don't always hit the bullseye, you are accurate but not precise.
If you hit the bullseye every time you shoot you are both accurate and precise.
If you hit a different part of the target every time you shoot, you are neither accurate nor precise.
If you hit the same area of the target every time but not the bullseye, you are precise but not accurate.

FIGURE 1.5.1 Using an archery target with arrows illustrates the difference between accuracy and precision. In summary, measurements should be both precise and as accurate as you can make them.

Recording numerical data

When using instruments to measure data, the number of significant figures (or digits) and decimal places you use is determined by how precise your measurements are.

The overall precision of the measurement depends on the scale, accuracy and precision of the instrument and technique you are using (Figure 1.5.2). For example, a beaker may be used to measure volumes approximately and has limited accuracy of, for example, ±5%; however, a graduated pipette is much more accurate, with accuracies of ±0.1% or ±0.2%. Your pipette may be accurate but if your technique using the pipette is variable, the overall accuracy and precision will be limited.

When you record **raw data** and report processed data, you must use the number of significant figures available from your equipment or **observation**. (This is discussed in more detail in Module 1.10.) Using either a greater or smaller number of significant figures can be misleading. For example, Table 1.5.1 shows measurements of five mass samples taken using an electronic balance accurate to 2 decimal places. The data was entered into a spreadsheet to calculate the mean, which was displayed with 4 decimal places. You would record the mean as 20.83 g, not 20.8260 g, because 2 decimal places is the precision limit of the instrument. Recording 20.8260 g would be an example of false precision.

FIGURE 1.5.2 A 5 mL graduated pipette can measure volumes to an accuracy of one-tenth of a millilitre, or 5 mL ± 0.1 mL. The pipette has major divisions of 1 mL and minor divisions of 0.1 mL. You can estimate to 0.05 mL and record volumes to 2 decimal places, for example, 3.80 mL or 4.55 mL.

TABLE 1.5.1 An example of false precision in a data calculation

Sample	1	2	3	4	5	Mean
Mass (g)	20.13	20.62	21.22	20.99	21.17	20.8260

UNCERTAINTY AND ERROR

Uncertainty is a range of measurement from the experiment, within which the true value is expected to lie. Due to sources of error and uncertainty, an estimation is made to suggest where the true value should be found among the measurements. Uncertainty is one indicator of a limitation. Expressed as a ± value, uncertainty can be derived either from the known precision of the equipment or alternatively from calculations involving the range of trials (see 'measurement uncertainty' and 'uncertainty of the mean').

Errors

Error is the difference between a measurement and the true value. This is not an indication of human error or mistakes. It is due to an inability to achieve the true value. Error cannot be eliminated, and therefore it is important to understand and record the error and report it. Two types of errors can occur—systematic error and random error (Table 1.5.2).

TABLE 1.5.2 Systemic and random errors

Error	Definition	Cause	Example
systematic	An error in measurements caused by the design of a system (e.g. methodology) or instrument (uncalibrated), which results in the measurements shifting in a systemic direction. The mean may be displaced or varied in a predictable way affecting the accuracy of the measurement. It is quantified by calculating percentage error.	• instrument calibration (Figure 1.5.4) • choice of instrument • precision of instrument (increments) • precision of instrument (sample rate—per second) • sampling (the choice of population or representatives) • heat loss to the surroundings	The balance used for weighing out samples reads 0.05 g too high for all your masses (because it was improperly tared (set to zero) at the start of the experiment).
			A thermometer is not calibrated to the correct temperature. All temperatures will be slightly off by the same amount. If this amount can be determined, the data can be corrected.
random	An error that affects the measurement in an unpredictable way, resulting in an even variation (fluctuation) in measurements above and below the expected true value. This affects the precision of the measurement. It is quantified by calculating percentage uncertainty.	• estimation (measuring between increments) • sampling (frequency, spread, increments) • parallax (Figure 1.5.3) • instrument sensitivity • noise	Using a stopwatch to measure time involves the random reaction time and judgments of the measurer.
			Measuring an electric field using a sensor which also picks up random background noise from electronic devices in the room.

FIGURE 1.5.3 (a) The correct reading of 0 kg is obtained when the scale is viewed from directly in front. (b) An incorrect reading of 2 kg is obtained because of parallax error when reading an analog scale at an angle.

FIGURE 1.5.4 Three examples of zero error on analog instruments: (a) voltmeter (b) ammeter and (c) a digital instrument (an electronic balance)

Determining an uncertainty in a single measurement

When using an instrument to measure a property of an object, there will always be a limit as to how precise the reading can be. In a physics experiment, analog and digital instruments are both used and measurements are determined slightly differently depending on which device is used.

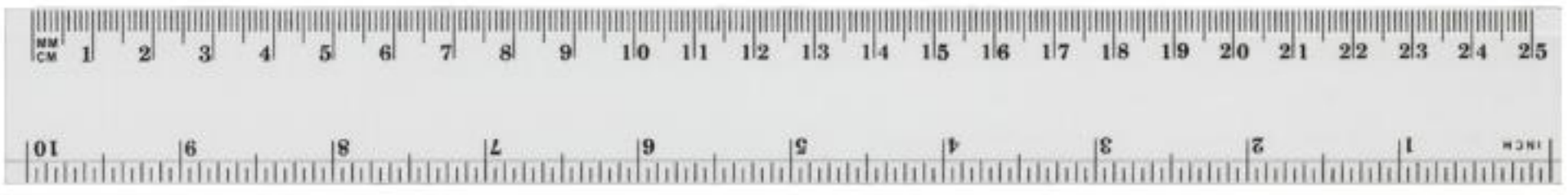
The precision that can be read off a single instrument is called the limit of reading. This is the smallest visible graduation on an analog instrument, or, if a digital instrument is used, then the limit of reading is usually the smallest decimal place given on the screen.

For most analog instruments, the absolute uncertainty, Δx, in a measurement of x is exactly half of the limit of reading for each part of the measured object that has to be lined up. This means that the actual measurement could be anywhere from half of the smallest graduation too big to half of the smallest graduation too small.

Some analog instruments have a zero mark and a reading mark, such as the ruler shown in Figure 1.5.5a. The object to be measured has to be lined up at both ends, therefore doubling the absolute uncertainty. For rulers and protractors, the absolute uncertainty is equal to the limit of reading, not half of it.

For a digital instrument, Δx is typically the limit of reading, or the smallest decimal place given on the screen. An example of this is a high-precision electronic balance, as shown in Figure 1.5.5b.

a



b

FIGURE 1.5.5 (a) The ruler has a limit of reading of 1 mm and (b) the electronic balance has a limit of reading of 0.001 g.

For analog instruments that have one scale to line up (such as a measuring cylinder, thermometer or voltmeter), the absolute uncertainty, Δx, in a measurement of x is exactly half of the limit of reading for each part of the measured object that has to be lined up.

For analog instruments that have two scales to line up (such as rulers and protractors) the absolute uncertainty, Δx, is equal to the smallest graduation scale, or limit of reading.

For digital instruments the absolute uncertainty, Δx, is equal to the smallest decimal place displayed.

Table 1.5.3 on page e38 summarises the limit of reading and absolute uncertainty of common analog instruments used in a high school physics laboratory.

TABLE 1.5.3 A summary of common instruments and their uncertainties used in a physics laboratory

Instrument	Type of instrument	Limit of reading	Absolute uncertainty	Example	Notes
mm ruler	analog	1 mm	± 1.0 mm	123.8 ± 1.0 mm	Half of the limit of reading is 0.50 mm, but the object to be measured has to be lined up at both ends, so the uncertainty is double this, or ±1.0 mm.
cm ruler	analog	1 cm	± 1.0 cm	31.4 ± 1.0 cm	As for a mm ruler.
Vernier callipers	analog	0.05 mm	0.05 mm	19.44 ± 0.05 mm	Vernier calipers and micrometers use screws to determine the measurement (shown in Figure 1.5.6).
micrometer	analog	0.01 mm	± 0.01 mm	7.13 ± 0.01 mm	
thermometer	analog	1.0°C	± 0.5°C	24.4 ± 0.5°C	Only the top part of the liquid in the thermometer has an uncertainty, so the uncertainty is exactly half of the limit of reading.
measuring cylinder	analog	1.0 mL	± 0.5 mL	15.7 ± 0.5 mL	The limit of reading and absolute uncertainty depend on the size of the measuring cylinder.
protractor	analog	1.0°	± 1.0°	30.1 ± 1.0°	The two lines that make up the angle have to be lined up, so the uncertainty is twice half of the limit of reading, similar to that in mm and cm rulers.
stopwatch	digital	0.01 s	from ± 0.1 to ± 0.4 s	9.6 ± 0.2 s	The limit of reading is not the absolute uncertainty for a stopwatch because the user's reaction time (usually between 0.1 and 0.4 s) needs to be taken into consideration.
electronic balance	digital	typically 0.01 g	± 0.01 g	7.03 ± 0.01 g	The absolute uncertainty is the smallest possible decimal place displayed.

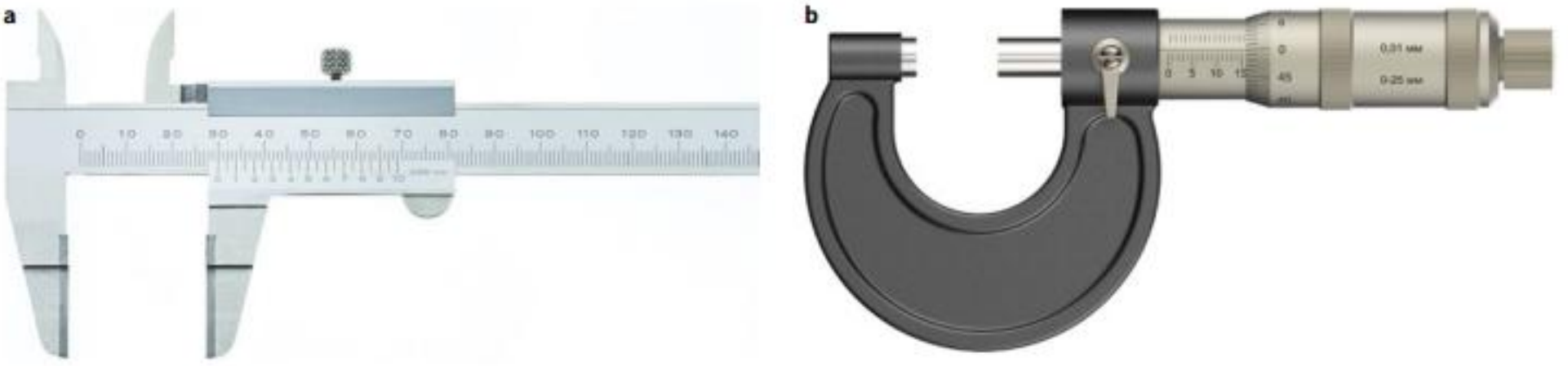


FIGURE 1.5.6 (a) A Vernier calliper and (b) micrometer use screws to determine the measurement.

Uncertainties and errors should always be calculated or measured and then reported. They then form part of the analysis and interpretation (see Module 1.7 Data analysis) as well as the evaluation. Also, it is a good idea to consider uncertainty and error when planning experiments (see Part B: Student experiment).

SKILLBUILDER 1.5.1

Calculating absolute measurement uncertainty

Calculate the absolute measurement uncertainty for instrumental error during an experiment where the temperature was measured at 32°C using a glass thermometer with increments of 1 degree Celsius and also a digital thermometer with increments of 0.1 degree Celsius.

For the glass thermometer

1 Write down the formula.

2 Insert the values and calculate.

3 Combine the measurement with the uncertainty.

32°C ± 0.5°C

For the digital thermometer

1 Write down the formula.

uncertainty = smallest increment

2 Insert the values and calculate.

uncertainty = 0.1

3 Combine the measurement with the uncertainty.

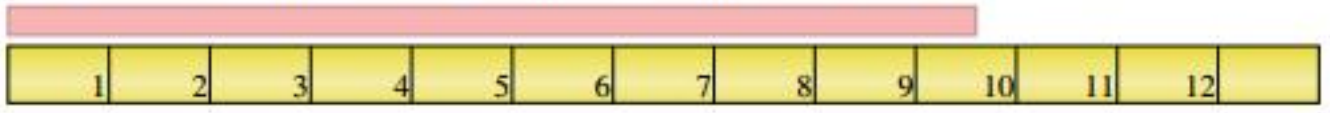
32.0°C ± 0.1°C

Worked example 1.5.1

READING MEASUREMENTS

For each of the following objects, determine its measurement and uncertainty.

a The length of the pink rectangle is measured with a ruler calibrated in cm.



Thinking	Working
The pink rectangle is between 9 cm and 10 cm in length, so the best estimate for this is 9.6 cm.	Length $L = 9.6\,\text{cm}$
The limit of reading is 1.0 cm so this is the uncertainty in a cm ruler.	$\Delta L = \pm 1.0\,\text{cm}$
Write the measurement and the uncertainty.	Length = 9.6 ± 1.0 cm

b The temperature of tap water is measured using an analog thermometer.

Thinking	Working
The temperature is between 40.1°C and 40.2°C, with the best estimate of 40.14°C.	Temperature $T = 40.14\,°\text{C}$
The limit of reading is 0.1°C so the uncertainty is half of this: 0.05°C.	$\Delta T = \pm 0.05\,°\text{C}$
Write the measurement and uncertainty.	$T = 40.14 \pm 0.05\,°\text{C}$

c The temperature of a bucket of tap water is measured using a digital thermometer.

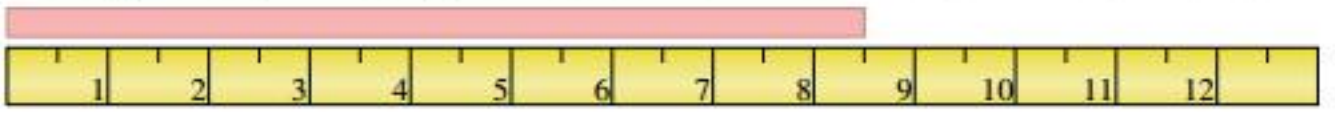
Thinking	Working
This temperature measurement is done using a digital thermometer, so the temperature is simply read off the screen at 36.4°C.	Temperature $T = 36.4°C$
The uncertainty in this measurement is then 1 of the smallest decimal value: ± 0.1°C.	$\Delta T = \pm 0.1°C$
Write the measurement and uncertainty.	$T = 36.4 \pm 0.1°C$

➤ Try yourself 1.5.1

READING MEASUREMENTS

For each of the following objects, determine its measurement and uncertainty.

a The length of the pink rectangle is measured with a ruler calibrated in half-cm intervals.



b The volume of the liquid is measured in a measuring cylinder calibrated in mL.

c The mass of this apple is measured on an electronic balance.

Determining an uncertainty in several trials of a measurement

The information above described how to determine the absolute uncertainty in a single measurement. To reduce the absolute uncertainty of a measurement, take as many trials as possible of the same measurement.

Once a series of trials of a single measurement has been taken, the best estimate of the value of the quantity is the average, or mean:

$$x_{best} = \bar{x} = \frac{\text{sum of the individual trials, } x_1, x_2, \ldots}{\text{number of trials, } n} = \frac{\sum x}{n}$$

The absolute uncertainty of the mean, $\Delta\bar{x}$, is found by finding the difference between the smallest and largest individual trials, then dividing by 2:

$$\Delta\bar{x} = \pm\left(\frac{x_{max} - x_{min}}{2}\right)$$

Note that if the absolute uncertainty of the mean gives a smaller value than the individual absolute uncertainties, then the absolute uncertainty of the mean should be the absolute uncertainty of the individual measurements.

$$\text{uncertainly} = \pm\frac{\text{upper value} - \text{lowest value}}{2}$$

> **For a series of trials of a single measurement, the best estimate of the measurement is the mean, or average, and the best estimate of its uncertainty is the absolute uncertainty of the mean.**

Worked example 1.5.2

CALCULATING UNCERTAINTY

The thickness, t, of a copper wire was measured along six points and recorded in mm (using a micrometer with an uncertainty of ± 0.01 mm) as:

5.84, 5.83, 5.82, 5.85, 5.79, 5.81

Calculate the mean (average) value for the thickness of the copper wire and its absolute uncertainty.

Thinking	Working
First, calculate the mean of the set of measurements.	$t = \frac{5.84 + 5.83 + 5.82 + 5.85 + 5.79 + 5.81}{6}$ $= \frac{34.94}{6}$ $= 5.82\text{mm}$
Write down the formula for absolute uncertainty.	$\Delta\bar{x} = \pm\left(\frac{x_{max} - x_{min}}{2}\right)$
Substitute into the formula to find the uncertainty in the mean.	$\Delta t = \pm\left(\frac{5.85 - 5.79}{2}\right)$ $= \pm\left(\frac{0.06}{2}\right)$ $= \pm 0.03\text{ mm}$
This value is larger than each individual uncertainty (0.01), so it will now be the final absolute uncertainty of the mean. Combine the mean and the uncertainty in the final answer.	$t = 5.82 \pm 0.03\text{mm}$

➤ Try yourself 1.5.2

CALCULATING UNCERTAINTY

The masses, *m*, of five pendulum bobs taken from the same batch were measured using an electronic balance set to grams:

24.66 g, 24.59 g, 24.51 g, 24.76 g, 24.75 g

Calculate the mean (average) mass of the pendulum bobs and the absolute uncertainty in the mean.

Calculating percentage error in values

As stated above, scientist try to calculate the 'true' or 'correct' value. However, due to uncertainties in the measurements experimental results may result in an inaccurate value. The density of water is generally stated to be 1 kg m^{-3}; however, the exact density at 4.0 °C is 0.9998395 kg m^{-3}.

The difference between the true value and the generally accepted value can be calculated using the percentage error formula, as shown in worked example 1.5.2.

In this case the measured value is replaced with the accepted value. The percentage error in the accepted (rounded) value of 1 kg m^{-3} is less than 0.02 %. This indicates that using 1 kg m^{-3} is acceptable since the percentage error is very small and likely to be much smaller than experimental uncertainty.

Percentage uncertainty

The absolute uncertainty of a measurement expresses the uncertainty in the readings. This reflects the precision of the measurement.

Measurements are quantified by associating them with uncertainty. For example, the best estimate of a volume is 5.0 cm^3, but due to uncertainty, the volume might be as small as 4.9 cm^3 or as large as 5.1 cm^3. In this example, the absolute uncertainty in the volume is ±0.1 cm^3.

Uncertainty can also be reported as a percentage of the measurement; this is known as **percentage uncertainty**. To calculate the percentage uncertainty, apply this formula:

$$\text{percentage uncertainty (\%)} = \frac{\text{absolute uncertainty}}{\text{measurement}} \times 100\%$$

It is important to not confuse percentage uncertainty with percentage error which was introduced at the beginning of module 1.5. Percentage error expresses the difference between the measured value and the accepted value. This reflects the accuracy of the measurement. Unlike percentage uncertainty, which can be determined for any measurement, percentage error can only be determined if an accepted value (such as the speed of light) is known.

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true valued}}\right| \times 100\%$$

The percentage uncertainty is a way of writing the uncertainty of a measurement as a percentage of the measurement.

The percentage uncertainty reflects the precision of a measurement, that is, how far it is from other measurements of the same thing. The percentage error reflects the accuracy of a measurement, that is, how far it is from an established or true value.

Worked Example 1.5.3

CALCULATING PERCENTAGE UNCERTAINTY FOR INSTRUMENTAL ERROR

The temperature during an experiment was measured and then reported at 32.00°C ± 0.05°C. Calculate the percentage uncertainty.

Thinking	Working
Write the formula for percentage uncertainty.	$\text{percentage uncertainty} = \pm\left\lvert\frac{\text{absolute uncertainty}}{\text{measurement}}\right\rvert \times 100\%$
Insert the values and calculate.	$\text{percentage uncertainty} = \pm\left\lvert\frac{0.05}{32}\right\rvert \times 100\%$ $= 0.16\ \%$
Combine the measurement with the percentage uncertainty and express to the appropriate number of significant figures.	32.00°C ± 0.16%

➤ Try yourself 1.5.3

CALCULATING PERCENTAGE UNCERTAINTY FOR INSTRUMENTAL ERROR

A ray of light was bent through a prism by an angle of 11.4 ± 0.6 degrees. Calculate the percentage uncertainty.

Significant figures

Another way of describing precision is by the number of **significant figures** in a measurement. The significant figures of a measurement are digits that are known exactly. The more significant figures a measurement has, the higher its precision.

When measuring phenomena during experimentation, the precision of the instruments determines the number of significant figures and decimal places you record in the data. Significant figures convey meaning and precision and the number of significant figures used depends on the scale of the instrument. You should record data using the number of significant figures available from the equipment or observation. Using either a greater or smaller number of significant figures is misleading. Significant figures are the exact digits observed when recording the results of an observation or experiment. For example, if the distance travelled by an object in 20 seconds was 6.0 m because exactly 6.0 m was observed, then the measurement is 6.0 m with 2 significant figures, not 6 m. Table 1.5.3 shows some examples of measurements and how many significant figures they have.

TABLE 1.5.3 Measurements and significant figures

Measurement	Number of significant figures
4.2003 × 10^{-5}	5
1.9 × 10^{23}	2
3.500 × 10^{2}	4
6 × 10^{24}	1
15	2
3.5	2
3.50	3
0.0**37**	2
1401	4
1400	2

> **i** It is important to record the exact numbers measured during an experiment. This determines the significant figures, and later the accuracy and precision of the analysis. If a zero is observed, record it, as it is the exact amount measured. This includes all zeros before and after decimal places.

Using either a greater or smaller number of significant figures can be misleading. For example, Table 1.5.4 shows three measurements to 2 decimal places (4 significant figures). The data was entered into a spreadsheet to calculate the **mean**, which was displayed with 3 decimal places. You would record the mean as 19.52 mL, not 19.517 mL, because 2 decimal places is the precision limit of the instrument. Recording 19.517 g would be an example of false precision.

TABLE 1.5.4 An example of false precision in a data calculation

Trial	1	2	3	Mean
Volume (mL)	19.45	19.55	19.55	(19.517)

When writing an answer to the correct number of significant figures, you may need to use rounding if the initial answer has more figures (digits) than you need. These extra figures are called 'non-significant figures'. If the first non-significant figure is ≥5, round up the number. If the first non-significant figure is <5, then do not round up. For example, if the initial answer for a calculation was 2.1259 but you only needed an answer to 3 significant figures, you would round it to 2.13. If the initial answer was 2.1241, then to 3 significant figures, this becomes 2.12.

SKILLBUILDER 1.5.2

Identifying significant figures

When giving an answer to a calculation, it is important to take note of the number of significant figures that you use.

You should give an answer that is as accurate as possible. However, an answer cannot be more accurate than the data or the measuring device used to calculate it. For example, if an electronic balance that measures to the nearest gram shows that an object has a mass of 56 g, then the mass should be recorded as 56 g, not 56.0 g. This is because you do not know whether it is 56.0 g, or 56.1 g, or 56.2 g or 55.8 g.

The number 56 has 2 significant figures. Recording to 3 significant figures (e.g. 56.0 g or 55.8 g) would not be scientifically 'honest'.

If this mass of 56 g is used to calculate another value, it would also not be 'honest' to give an answer that has more than 2 significant figures.

Determining the number of significant figures to give an answer to depends on the kind of calculation you are doing.

- If you are multiplying or dividing, use the smallest number of significant figures provided in the initial values.
- If you are adding or subtracting, use the smallest number of decimal places provided in the initial values.

Working out the number of significant figures

Use the following rules to avoid confusion in determining how many significant figures are in a number.

- All digits (including 0) in the coefficient of a number written in scientific notation are significant.
- All non-zero digits are always significant; for example, 21.7 has 3 significant figures.
- All zeros between two non-zero digits are significant; for example, 3015 has 4 significant figures.
- A zero to the right of a decimal point and following a non-zero digit is significant; for example, 0.5700 has 4 significant figures.
- Any other zero is not significant, as it will be used only for locating decimal places; for example, 0.005 has just 1 significant figure.

Worked example 1.5.4

IDENTIFYING SIGNIFICANT FIGURES

Determine how many significant figures there are in these measurements.

a 8.07×10^{14} kg

b 9.00 m

c 0.000 100 3 s

d 4560 N

Thinking	Working
a This measurement is written in scientific notation; therefore, all digits in the coefficient are significant.	3 significant figures
b The final zeros are significant, as they did not need to be written down unless they were specifically measured.	3 significant figures
c The first four zeros are not significant as they are just placeholders. The middle zeros are significant because they are located between two non-zero digits.	4 significant figures
d The final zero is not significant, or is ambiguous, so it is not counted.	3 significant figures

➤ Try yourself 1.5.4

SIGNIFICANT FIGURES

Determine how many significant figures there are in these measurements.

a 77000T
b 0.000000422
c 2.76×10^{-17}C
d $20.040\,m\,s^{-2}$

Calculations with uncertainties

There are a few rules when conducting calculations with numbers (or measurements) that have uncertainties. It is important to record the correct uncertainty once all the calculations are done so that the appropriate accuracy is reported. Table 1.5.5 outlines the rules for undertaking calculations with data and its associated uncertainty.

Keep in mind that the rules for significant figures apply to all numerical reporting, including the uncertainties.

TABLE 1.5.5 Rules for calculations involving uncertainty

Calculation	Rule	Examples
addition and subtraction	add the absolute uncertainties	$5.4 \pm 0.05 + 3.2 \pm 0.05 = 8.6 \pm 0.1$ $5.4 \pm 0.05 + 3.2 \pm 0.1 = 8.6 \pm 0.15$ $5.4 \pm 0.05 - 3.2 \pm 0.05 = 2.2 \pm 0.1$ $5.4 \pm 0.05 - 3.2 \pm 0.1 = 8.6 \pm 0.15$
multiplication and division	add the percentage uncertainties	$3.0 \pm 0.05 \times 1.5 \pm 0.05$ $= 3.0 \pm 1.6\% \times 1.5 \pm 3.3\% = 4.5 \pm 4.9\%$ $3.0 \pm 0.05 \div 1.5 \pm 0.05$ $= 3.0 \pm 1.6\% \div 1.5 \pm 3.3\% = 2.0 \pm 4.9\%$
multiplying by a constant (absolute uncertainty)	multiply the uncertainty	$3.14 \times (4.1 \pm 0.05) = 12.9 \pm 0.16$
multiplying by a constant (percentage uncertainty)	maintain the uncertainty	$3.14 \times (4.1 \pm 1.6\%) = 12.9 \pm 1.6\%$
Indices	Multiply the percentage uncertainty by the absolute value of the index	$(2.20 \pm 0.05)^2 = (2.20 \pm 2.2727\%)^2$ $= 4.84 \pm (2 \times 2.2727)\% = 4.84 \pm 4.54\%$ $= \sqrt{6.25 \pm 0.01} = \sqrt{6.25 \pm 0.16\%}$ $= 2.5 \pm (0.5 \times 0.16\%) = 2.5 \pm 0.08\%$

Note that addition, subtraction, multiplication, division, powers and square roots are the only operations that require you to work out the uncertainties. Other functions such as sin, cos and tan require the use of calculus, so you will not need to directly calculate the uncertainties of these operations in this course.

When propagating uncertainties with a mixture of addition, subtraction, multiplication, division and indices, perform the addition and subtraction calculations first, then the multiplication, division and power calculations.

Worked example 1.5.5

ADDING OR SUBTRACTING UNCERTAINTIES

Perform the following calculation: $(2.6 \pm 0.5)\,\text{cm} + (2.8 \pm 0.5)\,\text{cm}$	
Thinking	**Working**
First ignore each uncertainty and add the measurements.	Let x be the sum of the two quantities. $x = 2.6 + 2.8 = 5.4\,\text{cm}$
This is an addition operation, so add the absolute uncertainties.	$\Delta x = 0.5 + 0.5 = 1.0\,\text{cm}$
The absolute uncertainty can have 2 significant figures here because the first digit is 1. The absolute uncertainty also has 1 decimal place so x will also have 1 decimal place.	$x = 5.4 \pm 1.0\,\text{cm}$

➤ Try yourself 1.5.5

ADDING OR SUBTRACTING UNCERTAINTIES

Perform the following calculation:
$(4 \pm 2)\,\text{N} - (5.33 \pm 0.05)\,\text{N}$

Worked example 1.5.6

MULTIPLYING OR DIVIDING UNCERTAINTIES

Perform the following calculation: $(6.2 \pm 0.5)\,\text{cm} \times (2.81 \pm 0.01)\,\text{cm}$		
Thinking	**Working**	
First ignore each uncertainty and multiply the measurements. Do not forget to operate on the units as well.	Let x be the product of the two quantities: $x = 6.2 \times 2.81 = 17.422\,\text{cm}^2$	
This is a multiplication operation, so the absolute uncertainties will need to be converted into percentage uncertainties.	$6.2 \pm 0.5\,\text{cm}$ $= 6.2 \pm \frac{0.5}{6.2} \times 100\%\,\text{cm}$ $= 6.2 \pm 8.06\%$	$2.81 \pm 0.01\,\text{cm}$ $= 2.81 \pm \frac{0.01}{2.81} \times 100\%\,\text{cm}$ $= 2.81 \pm 0.356\%$
The percentage uncertainties are now added.	$\Delta x\% = 8.06\% + 0.356\% = 8.416\%\,\text{cm}^2$	

And the percentage uncertainty is now converted back into an absolute uncertainty.	$\Delta x\% = 8.416\%$ of $17.422\,cm^2$ $= 8.416 \times 17.422$ $= 1.5\,cm^2$
The absolute uncertainty has 1 as its first digit, therefore one more digit can be quoted: $\Delta x = 1.5$. The absolute uncertainty also has 1 decimal place so x will also have 1 decimal place.	$x = 17.4 \pm 1.5\,cm^2$

➤ Try yourself 1.5.6

MULTIPLYING OR DIVIDING UNCERTAINTIES

Perform the following calculation:

$$\frac{(2.0 \pm 0.2)\,cm}{(3.0 \pm 0.6)\,s}$$

Worked example 1.5.7

MIXED UNCERTAINTY CALCULATIONS

If $a = 4.52 \pm 0.02\,m$ and $b = 2.0 \pm 0.2\,s$, then calculate c and its uncertainty when $c = a^2b^3$.

Thinking	Working
First, ignore each uncertainty and perform the calculation for c. Don't forget the units.	$c = 4.52^2 \times 2.0^3$ $= 163.4432\,m^2s^3$
This is a multiplication operation, so the absolute uncertainties need to be converted into percentage uncertainties.	$a = 4.52 \pm 0.02\,m$ $= 4.52 \pm \frac{0.02}{4.52} \times 100\%\,m$ $= 4.52 \pm 0.4425\%\,m$ $b = 2.0 \pm 0.2\,s$ $= 2.0 \pm \frac{0.2}{2.0} \times 100\%\,s$ $= 2.0 \pm 10\%\,s$
To obtain the final percentage uncertainty, the individual percentage uncertainties are multiplied by the powers of a and b given in the formula.	$\Delta c\% = 2 \times 0.4425\% + 3 \times 10\%\,m^2s^3$ $= 0.885\% + 30\%\,m^2s^3$ $= 30.885\%\,m^2s^3$
Now convert the percentage uncertainty into an absolute uncertainty.	$\Delta c = 30.885\%$ of 163.4432 $= \frac{30.885}{100} \times 163.4432$ $= 50.48\,m^2s^3$
The absolute uncertainty does not have 1 as its first digit, therefore it must be rounded to 1 significant figure: $\Delta c = 50$. The absolute uncertainty therefore is written to the 10s placeholder, so c will also be written to the nearest 10s placeholder. An alternative to this is to write c and its uncertainty to the same power of 10.	$c = 160 \pm 50\,m^2s^3$ $= (1.6 \pm 0.5) \times 10^2\,m^2s^3$

➤ Try yourself 1.5.7

MIXED UNCERTAINTY CALCULATIONS

If $a = 3.6 \pm 0.6\,m$, $b = 9.91 \pm 0.01\,m$, and $c = 4.9 \pm 0.5\,kg$, calculate d when $d = \frac{a+b}{\sqrt{c}}$.

1.5 Review

SUMMARY

- All measurements made in physics experiments are subject to a level of uncertainty, or doubt, to the precision of that measurement.
- Systematic errors arise due to mistakes in calibrating or using equipment the wrong way for every measurement.
- Random errors are naturally occurring and cannot be eliminated.
- Accuracy is a description of how close a measurement is to an accepted value. To obtain accurate results, you must minimise systematic errors.
- Precision is a description of how close together a group of measurements are. To obtain precise results, you must minimise random errors.
- Uncertainty is a range of measurements from the experiment in which the true value is thought to be. A measurement without an uncertainty is meaningless.
- Error is the difference between a measurement and the true value; this is *not* an indication of human error or a mistake.
- Uncertainty and error values are presented as a range (e.g. ±0.3) or a percentage (±1.6%)
- The limit of reading of an instrument is the smallest graduation on the device.
- Analogue instruments with a single scale reading have an absolute measurement uncertainty equal to half the limit of reading. Analogue instruments with a double scale reading have an absolute uncertainty equal the limit of reading.
- Digital instruments have an absolute uncertainty equal to the limit of reading (the smallest decimal place displayed).
- The uncertainty in the average of several trials is given by:

$$\text{uncertainty} = \pm \frac{\text{upper value} - \text{lowest value}}{2}$$

$$\text{absolute uncertainty} = \pm \frac{\text{smallest increment}}{2}$$

$$\Delta\bar{x} = \pm\left(\frac{x_{max} - x_{min}}{2}\right)$$

- Percentage uncertainty is an indicator of precision. Percentage error is an indicator of accuracy and can only be applied when a theoretical or accepted result is known.
- Percentage uncertainty is given by:

$$\text{percentage uncertainty (\%)} = \pm \frac{\text{absolute uncertainty}}{\text{measurement}} \times 100\%$$

- Percentage error is given by:

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right| \times 100\%$$

- Significant figures are a way of communicating how precise a measurement is.
- The number of significant figures used depends on the scale of the instrument.
- There are specific rules governing how many significant figures there can be in any measurement.
  - All digits (including 0) in the coefficient of a number written in scientific notation are significant.
  - All non-zero digits are always significant.
  - All zeros between two non-zero digits are significant.
  - A zero to the right of a decimal point and following a non-zero digit is significant.
  - Any other zero is not significant.
- Propagation of uncertainties involves the mathematical combination of uncertainties from a range of variables.
- When adding or subtracting measurements, the individual absolute uncertainties always add.
- When multiplying or dividing measurements, the individual percentage uncertainties always add.
- When raising a measurement to a power, the percentage uncertainty is multiplied by the absolute value of the power.
- When using measurements in a formula, perform any addition and subtraction propagations first, followed by multiplication, division and indices.

KEY QUESTIONS

Describe

1 State the type of error associated with:
- **a** inaccurate measurements
- **b** imprecise measurements.

2 Identify whether each of the situations below is a mistake, a systematic error or a random error.
- **a** A student measured the lengths of three different wires using a cm ruler but did not check that the wire was lined up at the zero mark on the ruler.
- **b** A student was measuring the mass of approximately 2 g samples of 5-cent pieces using a balance that was accurate to the nearest 1 g.
- **c** A student sometimes forgot to rezero the balance between weighing trolleys used in a motion experiment.

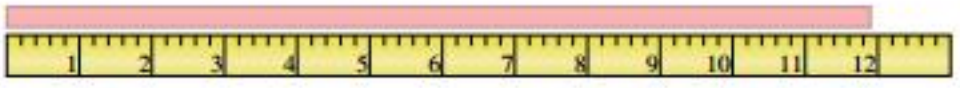
3 State the absolute uncertainty of the following instruments.
- **a** a cm ruler
- **b** a protractor graduated in degree intervals
- **c** an electronic balance giving a reading down to the nearest 0.001 g
- **d** an analog needle voltmeter graduated in 10 volt intervals

Apply

4 Explain why it would be unreasonable to state that the absolute uncertainty in a handheld stopwatch is ± half of the limit of reading, or ± 0.005 s.

5 Explain why repeated measurements do not change the systematic error.

6 Determine the length, and absolute uncertainty, of the pink rectangle using the given scale calibrated in cm.



7 Write these measurements and uncertainties to the correct number of significant figures and decimal places.
- **a** $(9.11 \times 10^{-31}) \pm (2.2345 \times 10^{-31})$ kg
- **b** $(0.0023456 \pm 1.623 \times 10^{-4})$ s

Analyse

8 Calculate the average and uncertainty of the two sets of data below.
Data set A: 11.4, 10.9, 11.8, 10.6, 11.5, 11.1
Data set B: 25.3, 27.4, 22.0, 26.1, 28.4, 23.1

9 Differentiate between precision and accuracy.

10 A friend asks to borrow your precious diamond for a day to show her family. You are a bit worried, so you carefully weigh your diamond on a scale that reads 8.17 g. The scale's precision is claimed to be ±0.05 g. The next day you weigh the returned diamond again, getting 8.09 g. Determine if this is your diamond.

11 The electrical power, P, dissipated by a resistor in an electrical circuit is given by:
$P = I^2 R$
where
I is the current (A)
R is the resistance (Ω).
If the percentage uncertainty in I is ±7% and the percentage uncertainty in R is ±10%, calculate the percentage error in P.

12 If $a = 20.0 \pm 0.5$ m and $b = 5 \pm 1$ m, calculate the value and absolute uncertainty of $c = 2a - b$.

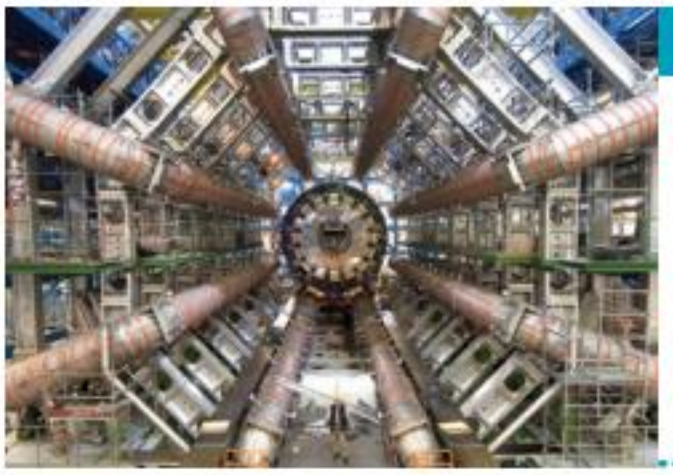
13 Calculate C and ΔC, if $C = 2\pi r$ and $r = 4.12 \pm 0.05$ m.

14 The density of an object is found by dividing its mass by its volume. An iron cube had its side length and mass measured five times.

Mass (±0.01 g)	121.37	121.40	121.39	121.36	121.38
Side length (±0.05 cm)	2.47	2.49	2.48	2.47	2.50

Calculate the following values, including the absolute uncertainty:
- **a** average mass
- **b** average side length
- **c** volume of the cube
- **d** density of the cube.

1.6 Tables and graphing



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- create tables to record and organise data
- appreciate that graphs can show a wealth of information relating two or more variables and constants, including their uncertainties
- understand that graphs can be used to predict relationships between variables or used to find outliers in data
- recognise the common types of graphs or relationships seen in physics and know examples of each

PRESENTING DATA IN TABLES

Tables record number values and allow you to organise your data. In general, tables provide more detailed data than graphs, but it is easier to observe trends and patterns in data when they are in graph form than when they are in table form.

Presenting raw data in tables

Tables organise data into rows and columns, and can vary in complexity according to the nature of your data. Tables can be used to organise raw data and **processed data**, or to summarise results. The first column of a table should contain the independent variable (the one you control) subsequent columns should contain trials of the dependent variable (the one that may change in response to a change in the independent variable).

As you can see in Figure 1.6.1, tables should have the following features:

- a descriptive title
- column headings (including the units)
- aligned figures (align the decimal points)
- the independent variable placed in the left column.

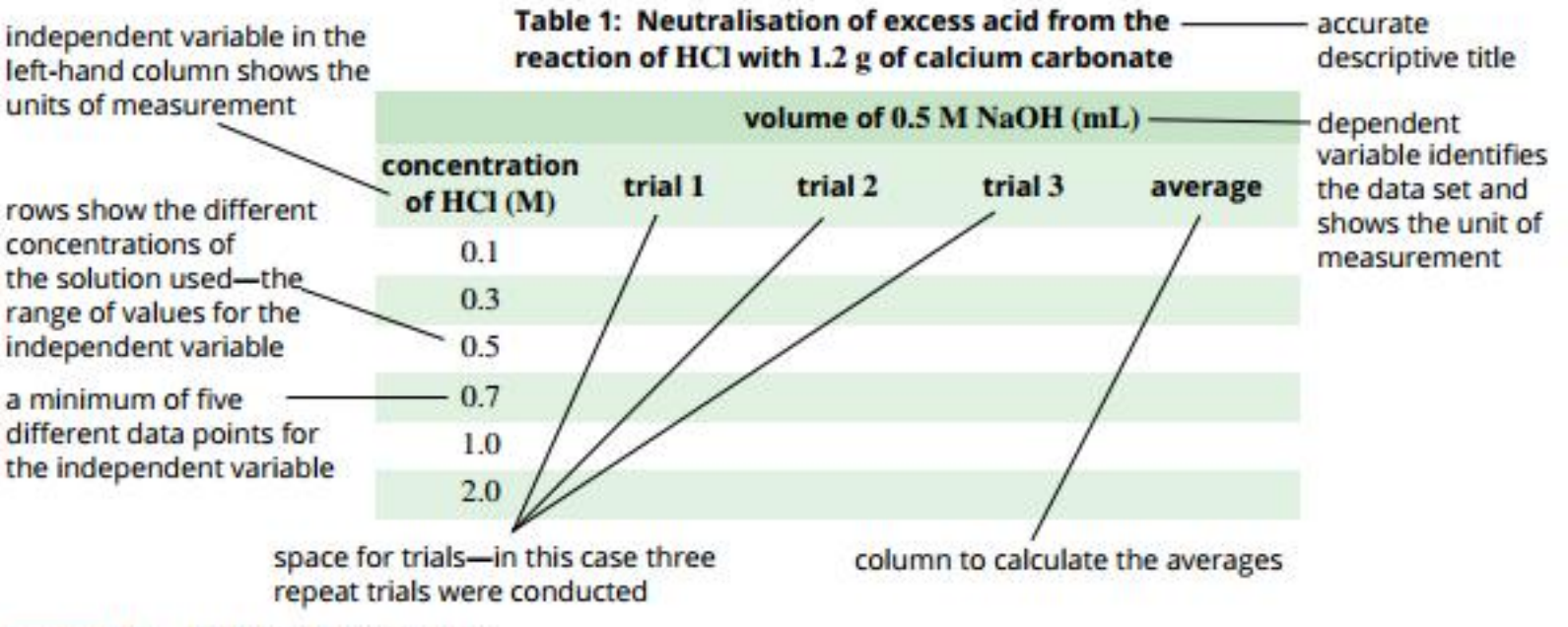


Table 1: Neutralisation of excess acid from the reaction of HCl with 1.2 g of calcium carbonate
accurate descriptive title
independent variable in the left-hand column shows the units of measurement
volume of 0.5 M NaOH (mL)
dependent variable identifies the data set and shows the unit of measurement
concentration of HCl (M)
trial 1
trial 2
trial 3
average
rows show the different concentrations of the solution used—the range of values for the independent variable
0.1
0.3
0.5
0.7
1.0
2.0
a minimum of five different data points for the independent variable
space for trials—in this case three repeat trials were conducted
column to calculate the averages

FIGURE 1.6.1 Features of a good table

PRESENTING DATA IN GRAPHS

A **graph** is an incredibly useful tool. In physics, data is plotted using a line or curved graph and it is sometimes called a scatterplot.

Plotting data in graphs has many advantages.

- Data can be represented visually.
- Data points that are deemed to be outliers can be ignored.
- Constants can be determined from the properties of the line or curve.
- Uncertainties can be represented as **error bars**.
- A general **line of best fit** that matches the trend of the majority of the data points can be determined.
- The uncertainty in the gradient and intercept can be propagated using a line of minimum fit and a line of maximum fit (see 1.7 Data analysis).
- Any known relationship between the dependent and independent variables can be supported or rejected, especially by the use of uncertainties.

Tables often provide more detailed data than graphs, but graphs can suggest a possible relationship between the dependent and independent variables, and highlight if none exists. From the shape of the curve, it is easier to observe trends, patterns and gaps in data in graphical form than in tabular form.

Graphs, like that shown in Figure 1.6.2, are used when two variables are being considered and one variable is dependent on the other. The graph shows the relationship between the variables.

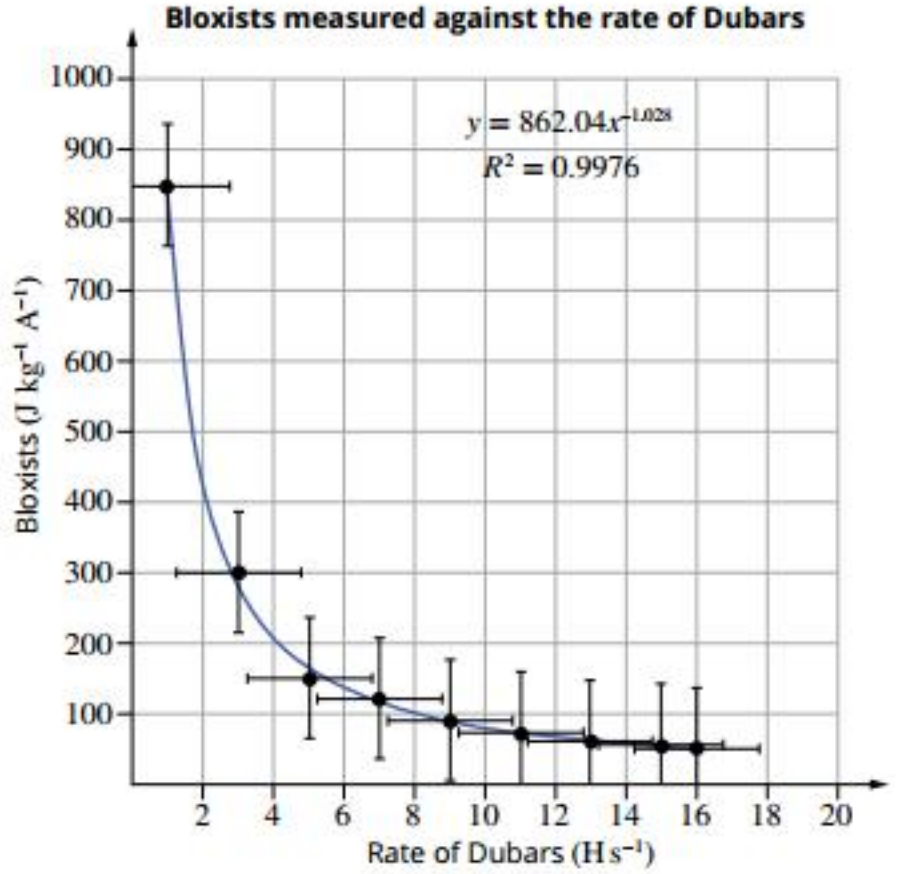


FIGURE 1.6.2 A graph showing the relationship between two variables: current (dependent variable) and voltage (independent variable)

DRAWING GRAPHS IN PHYSICS

For use in physics, every graph must have the following features:

1 The graph must have a suitable set of axes for the independent and dependent variables.

Most physics graphs are only drawn in the first quadrant, but some graphs use all four quadrants (i.e. have negative values for the independent and dependent variables).

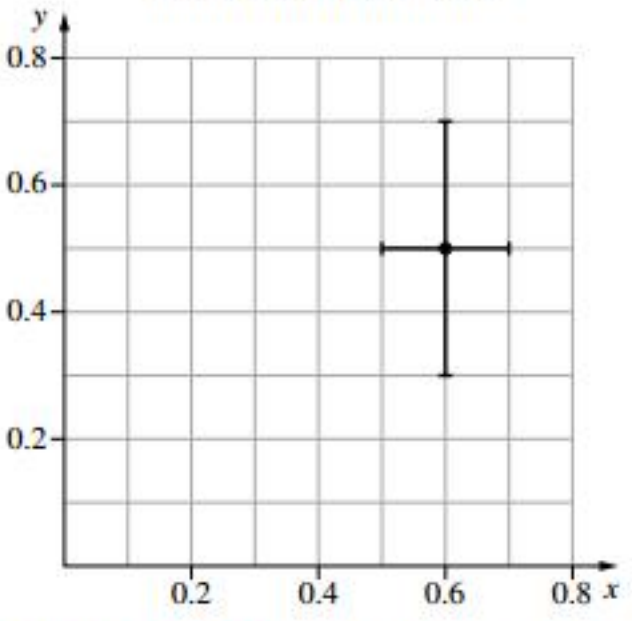


FIGURE 1.6.3 This error bar has an x value of 0.6 ± 0.1 and a y value of 0.5 ± 0.2.

Error bars are the graphical representation of the uncertainties in the independent and dependent variables.

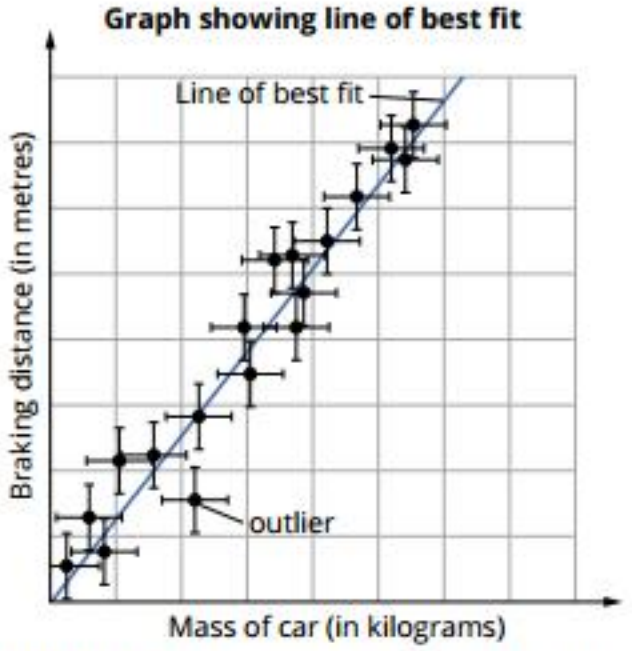


FIGURE 1.6.4 This graph shows that the line of best fit should normally pass through the error bars of each point and be extrapolated so that it intersects the y-axis.

The line of best fit is a straight line or curved line that best summarises the general pattern of the data on the graph.

Remember that:

- the independent variable is the variable that you deliberately change and always goes along the *x*-axis
- the dependent variable is the variable that changes and always goes on the *y*-axis.

2 The graph must have a suitable scale that allows information to be seen easily and quickly.

For most graphs, it is important to choose a scale that is linear and has tick marks at common intervals (e.g. 2, 5, 10, 100 units).

3 The title and axes must have labels. Make sure that the axis labels show information about the quantity and units. Give a descriptive title that is not just a repeat of the labels of the axes.

4 Data points should be plotted as a small circle or small cross indicating their position.

5 Error bars should be drawn for each point. These indicate the absolute uncertainties in the independent (a horizontal line) and dependent (a vertical line) values. They are drawn as a horizontal line centred on the data point indicating the independent variable's uncertainty left and right of the value, and as a vertical line centred on the data point above and below the value, indicating the dependent variable's uncertainty. Combining the *x* and *y* error bars forms an error rectangle that the true measurement is located within (Figure 1.6.3).

The smaller the errors bars for a given point, the more precise the measurement is.

The line of best fit

This is the straight line or a curve that best summarises the data. This line does not have to pass through every point or the origin, but does have to be one smooth continuous line or curve and *not* a 'join the dots' line (Figure 1.6.4). Typically, the line of best fit should have as many points on the line as possible, but if this is not possible then it should have as many points above the line as there are below the line.

These are some of the general rules to follow when making a graph.

- Keep the graph simple and uncluttered.
- Use a descriptive title.
- Represent the independent variable on the *x*-axis and the dependent variable on the *y*-axis.
- Start each axis at zero.
- Match the length of the axes to the data.
- Clearly label axes with both the variable and the unit in which it is measured.
- Use small symbols such as circles or crosses for data points.
- Use different symbols for different data sets.

TYPES OF GRAPHS SEEN IN PHYSICS

There are several types of graphs, including line graphs and bar graphs. The best one to use will depend on the nature of the data. In physics, many relationships in the form of formulas and graphs are seen that exist between two variables. Each graph below shows some particular relationship between the independent and dependent variables that you will encounter at some stage during your Physics course.

Linear graphs

Straight line or linear graphs represent variables that have a constant rate of change and the power of each variable is 1. The gradient and *y*-intercept of a linear graph are calculated easily, as shown in Figure 1.6.5. The general equation of a straight line is:

$$y = mx + c$$

where

m is the gradient

c is the *y*-intercept.

Examples of linear relationships in physics include force against acceleration and momentum against velocity. Note that, if the *y*-intercept of the equation is zero, then the relationship between the *x*- and *y*-variables is said to be directly proportional and the equation is $y = mx$. The equation of the line in Figure 1.6.6 is $y = 2x$.

Linear graphs of the form $y = mx + c$ either increase (if the gradient is positive) at a constant rate, or decrease (if the gradient is negative) at a constant rate.

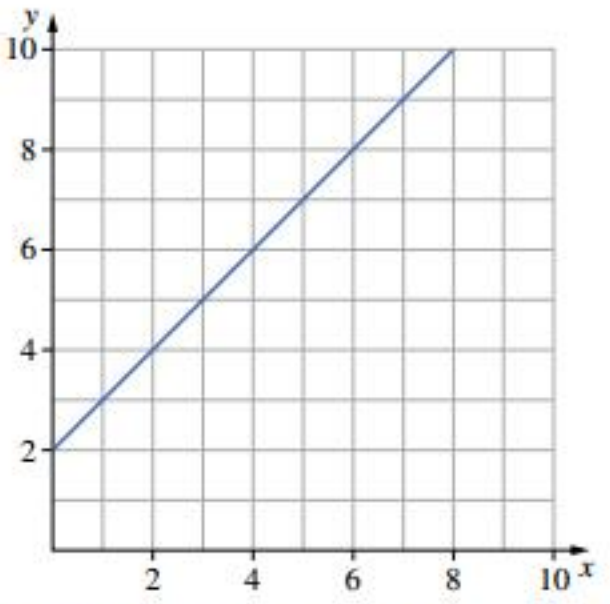


FIGURE 1.6.5 The linear, or straight line, graph. In this example, the equation of the line is $y = x + 2$, with a gradient of 1 and y-intercept of 2.

Parabolas

Parabolas represent relationships in which the independent variable is squared and the dependent variable increases at an increasing rate, as shown in Figure 1.6.7. The general equation of a parabola is:

$$y = kx^2$$

where k is a constant.

Examples of parabolic relationships in physics include kinetic energy against velocity and the position of a projectile against time, when launched at an angle to the horizontal.

Inverse functions or hyperbolas

These graphs represent variables with an inverse or $\frac{1}{\text{independent variable}}$ relationship. The curves decrease at a decreasing rate and do not intersect the *x*- or *y*-axes. When one variable increases, the other variable decreases, as shown in Figure 1.6.8. The general equation of a hyperbola is:

$$y = \frac{k}{x}$$

where k is a constant.

Examples of hyperbolic relationships in physics include pressure against volume, and object distance against image distance for a lens.

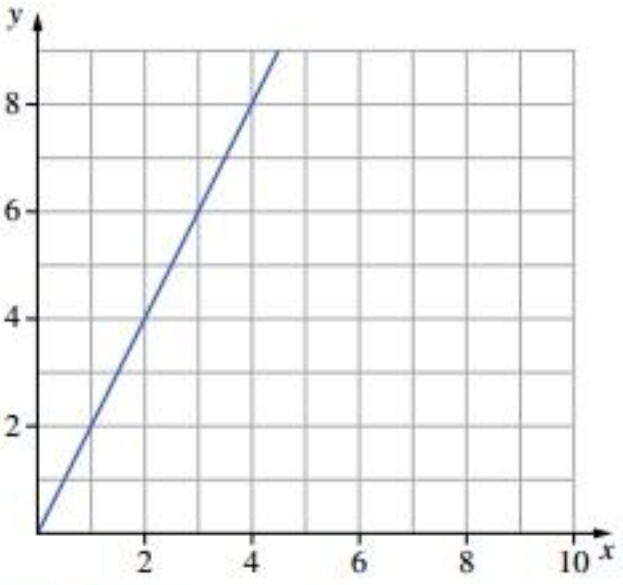


FIGURE 1.6.6 An example of a direct proportion. The equation of the line is $y = 2x$. The line passes through the origin and has a gradient of 2.

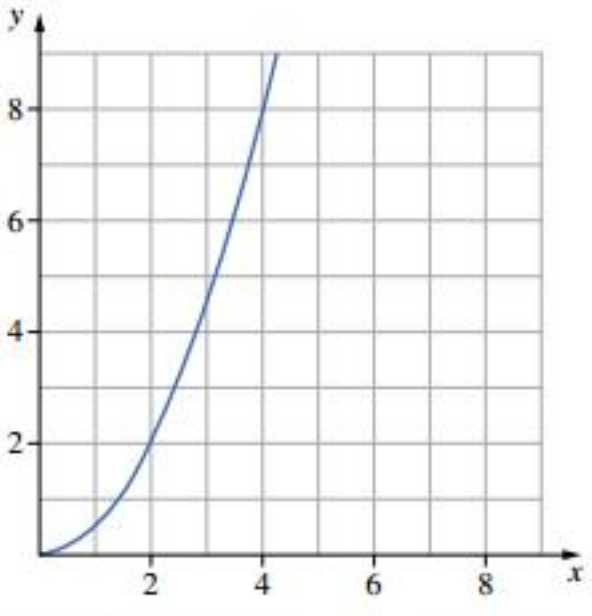


FIGURE 1.6.7 An example of a parabolic or squared graph. The equation of the parabola is $y = 0.5x^2$.

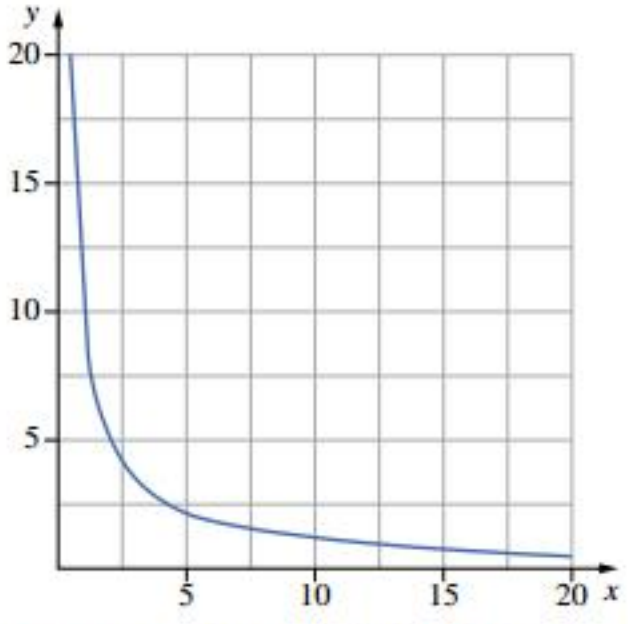


FIGURE 1.6.8 An example of a hyperbola, or inverse, graph. The equation of the hyperbola is $y = \frac{10}{x}$.

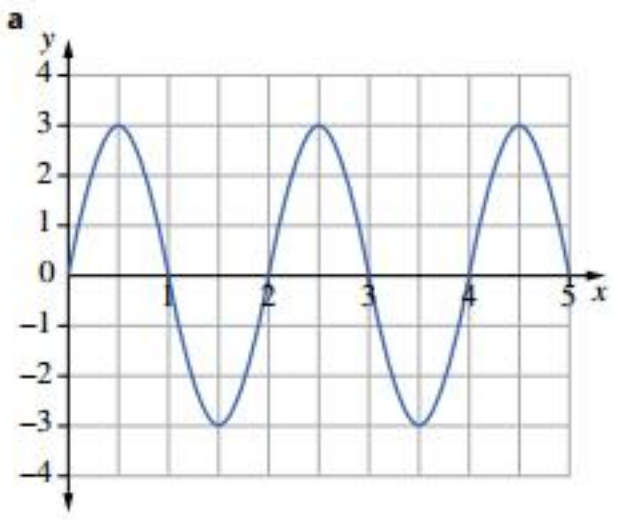


FIGURE 1.6.9 Examples of (a) a sine graph with equation $y = 3 \sin \pi x$ and (b) a cosine graph with equation of $y = 3 \cos \pi x$. The variable x is measured in radians in both cases.

Periodic or sine and cosine graphs

These graphs represent relationships that oscillate between a maximum and minimum value over a period of time, as shown in Figure 1.6.9. The general equations of a sine graph and a cosine graph are, respectively:

$$y = A \sin \omega x$$
$$y = A \cos \omega x$$

where

A is the amplitude, or the maximum value of y

ω is the angular frequency of the motion ($\omega = 2 \times \pi \times$ frequency).

Examples of sine and cosine relationships in physics include position versus time for a mass on a spring and current versus time for an alternating current supply.

Exponential decay

These graphs represent variables that decrease from an initial value over a period of time but never reach zero. The curves decrease at a decreasing rate, as shown in Figure 1.6.10. The equation of an exponential decay graph is:

$$y = Ae^{-kx}$$

where

A and k are constants

e is the mathematical constant 2.718 28...

Note that the exponential graph is different from an inverse relationship because an exponential relationship has a y-intercept, an inverse relationship does not.

An example of an exponential decay relationship in physics is the amount of decaying nuclear material remaining after a given time.

Square root graphs

These represent variables that increase but at a decreasing rate. This means that the dependent variable gets larger as the independent variable gets larger, but the difference becomes smaller and smaller. The equation for a square root graph (Figure 1.6.11) is:

$$y = k\sqrt{x}$$

where k is a constant.

Examples of where square root curves are used in physics are in the theoretical equation of the period of a pendulum and in many equations of relativity.

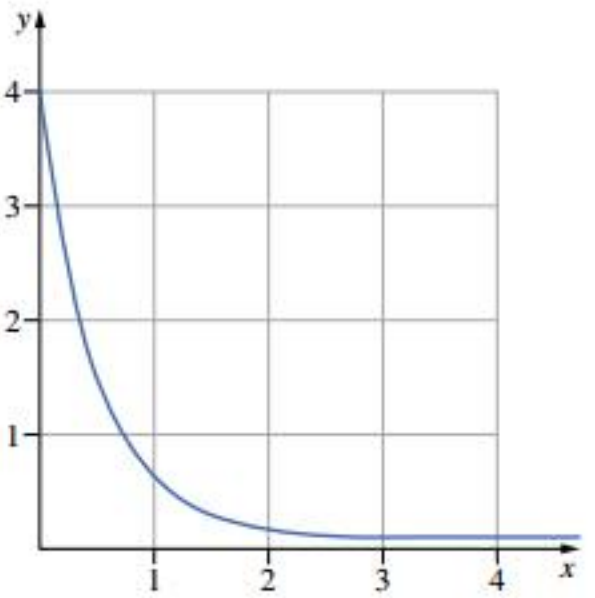


FIGURE 1.6.10 An exponential curve. In this example the equation of the curve is $y = 4e^{-x}$, indicating that the initial value of the graph is 4.

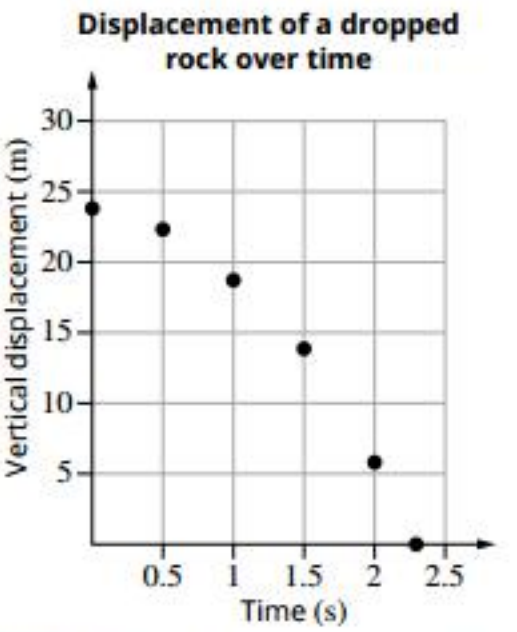


FIGURE 1.6.11 The square root curve. In this example the equation of the curve is $y = k\sqrt{x}$.

Table 1.6.1 summarises the common graphs seen in physics.

TABLE 1.6.1 A summary of the features of commonly encountered graphs and relationships seen in physics

Graph type	Basic equation	How y changes with x	Rate of change of y
directly proportional		increasing if $m > 0$ decreasing if $m < 0$	constant
linear		increasing if $m > 0$ decreasing if $m < 0$	constant
parabolic		increasing if $k > 0$, decreasing if $k < 0$	increasing
hyperbolic		decreasing	decreasing
periodic		oscillating between maximum and minimum	N/A
exponential		decreasing	decreasing
square root		increasing	decreasing

Outliers

Sometimes when you collect data, there may be one point that does not fit the trend and may be an error. This is called an **outlier**. An outlier is often caused by a mistake made in measuring or recording data, or from a random error in the measuring equipment. If you have an outlier in your results, you can include it in your graph but ignore it when drawing the line of best fit as in Figure 1.6.12.

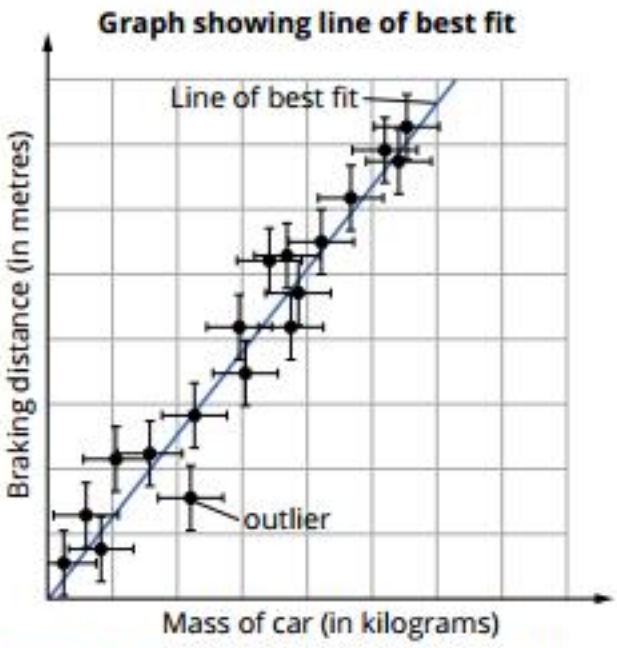


FIGURE 1.6.12 A scatter plot shows an outlier, which has been ignored when adding the line of best fit.

Distorting the truth

Poorly constructed graphs can distort the truth. For example, in Figure 1.6.13, you can see two graphs that show the same data—the test results of two groups of students. One group of students did not eat breakfast before doing the test and scored an average of 42 marks out of 50. The other group of students did eat breakfast and scored an average of 48 marks out of 50. One graph distorts the difference in marks between the two groups by using a scale of only 40 to 50 marks on the y-axis. It is important to make sure the graphs you create do not distort your data. You should also be wary of distorted data when interpreting graphs in other publications.

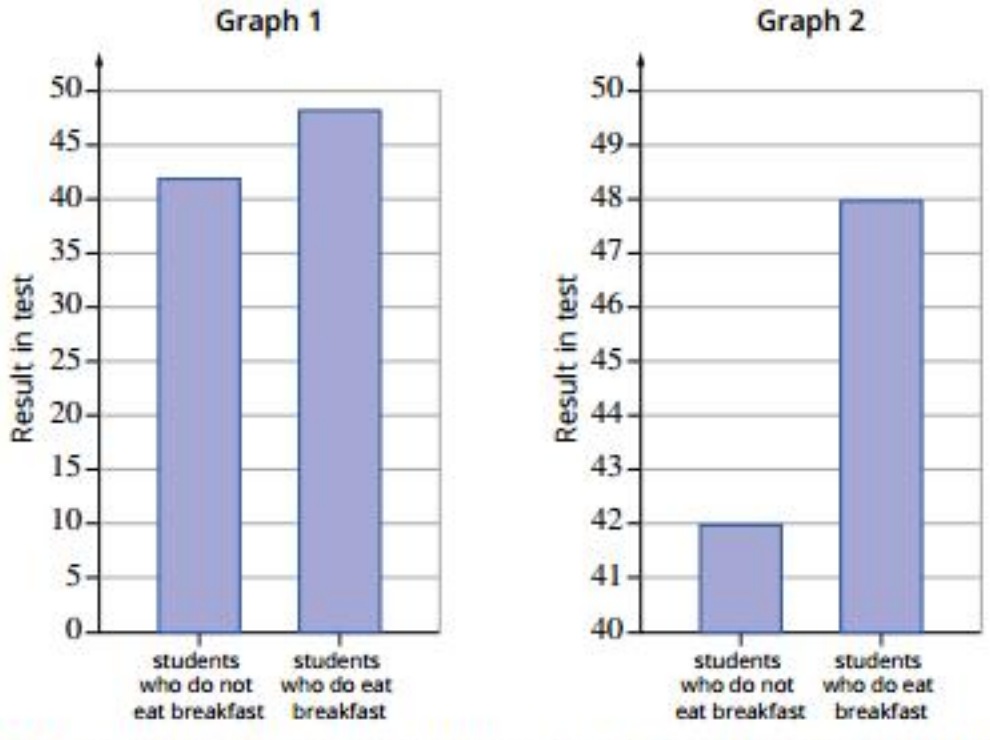


FIGURE 1.6.13 Graph 1 shows the difference between two groups of students out of the total 50 marks on the y-axis. Graph 2 shows the difference between the two groups within only a narrow range of marks on the y-axis, which distorts the difference and makes it appear larger than it really is.

1.6 Review

SUMMARY

- Tables and graphs are used to represent scientific data.
- In general, tables provide more detailed data than graphs, but it is easier to observe trends and patterns in data in graph form than in table form.
- Tables organise data into rows and columns, and can vary in complexity according to the nature of your data.
- Tables should have the following features:
  - a descriptive title
  - column headings (including the units and absolute uncertainty)
  - aligned figures (align the decimal points)
  - the independent variable placed in the left column
  - trials of the dependent variable placed subsequent columns
  - a column for the average
  - a column for uncertainty
- Graphs are used to display relationships, trends and patterns between two variables with one proposed to be dependent on the other.
  - Scatterplots are commonly used to display data in the form of a graph, and can be used for both raw and processed data.
  - Error bars indicate the absolute uncertainties in the independent and dependent values.
  - A trend line (line of best fit) is used to show the overall trend in the data, and can be used to predict values between the data points.
- An outlier is a data point that does not fit the trend, and may be caused by an error.

KEY QUESTIONS

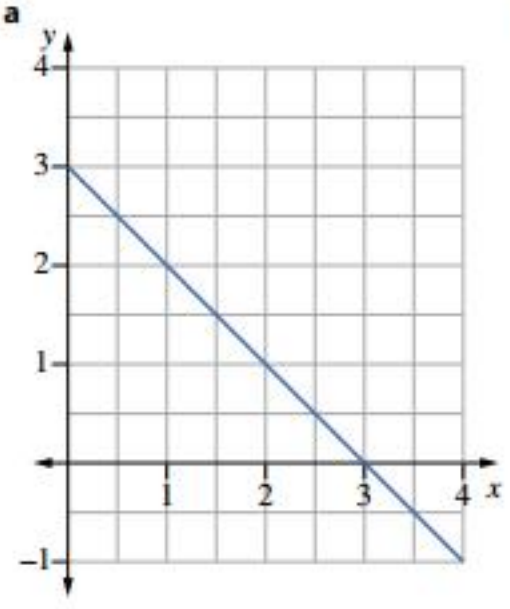
Describe

1 State the purpose of a trend line.

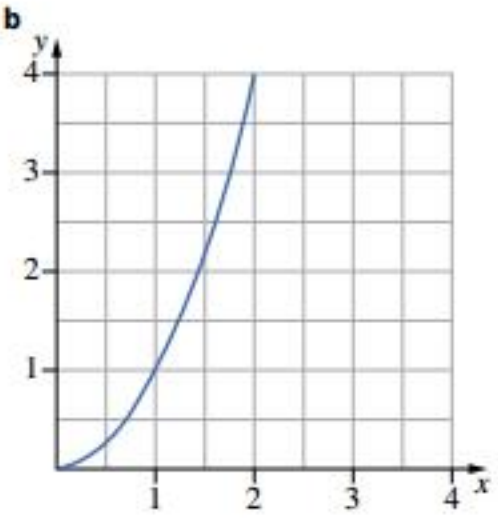
2 Recall how systematic errors are shown on a graph.

3 Identify the type of relationship between the *x*- and *y*-variables that is shown in the following graphs.

a



b



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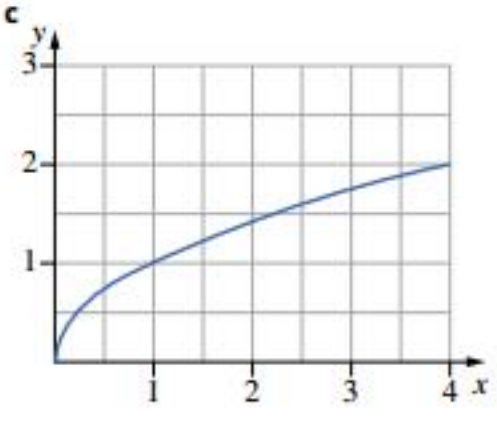
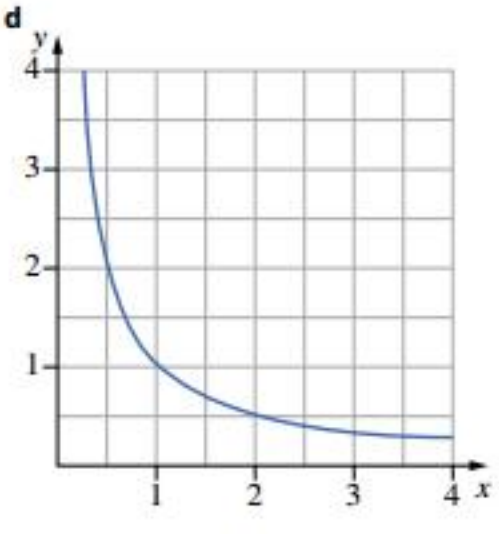


d



Apply

4 Explain what outliers are.

5 Identify the relationship between the variables indicated by a linear graph.

6 Identify the relationship that exists if one variable decreases as the other increases.

7 Describe the relationship that exists if both variables increase or both decrease at the same rate.

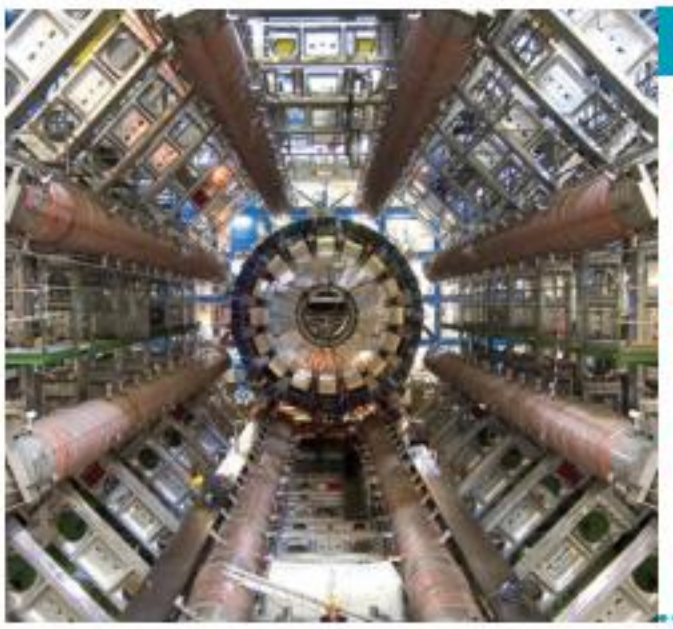
Analyse

8 If theory suggests that the *y*-intercept of a line is zero, deduce what this should look like on a linear graph.

9 Consider the data below and determine the relationship between atmospheric pressure and altitude.

Pressure (atm)	1.00	0.79	0.52	0.23	0.11	4.5×10^{-2}	1.3×10^{-2}	6.0×10^{-3}	2.1×10^{-3}
Altitude (km)	0	2.0	5.0	10.0	15.0	20.0	30.0	40.0	50.0

1.7 Data analysis



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- calculate and interpret the range, mean, median and mode of a set of data
- display data, including error bars, line of best fit, minimum and maximum lines of primary and secondary data
- use the R^2 values to evaluate the fit of a trend to a set of data.
- linearise data that is not already producing a straight line graph
- use the equation of a straight line of best fit to determine the gradient and *y*-intercept
- use the minimum and maximum lines to calculate an uncertainty in the gradient and *y*-intercept.
- use the gradient and *y*-intercept in further processing of data.

One of the difficulties in physics is that direct measurements of phenomena or measurements within a closed system are challenging to obtain. Therefore, the limitations and uncertainty in the data include uncertainties in the accuracy and precision of the measurements that were recorded as well as errors related to reliability and validity of the experimental procedure. To address this problem, physicists perform statistical analysis to help understand the quality of the measurements, the results and their meaning.

This module will outline a basic understanding of common statistical analysis used in physics relevant to the Physics General Senior Syllabus.

STATISTICAL MEASURES

There are several common statistical measures that help describe data accurately.

Range

The range is the difference between the highest and lowest values in a data set. Table 1.7.1 shows the measurements taken for two substances to come to thermal equilibrium.

TABLE 1.7.1 Time to reach thermal equilibrium for an aluminium block and 200 mL water initially at 20°C and 50°C

Temperature (°C)	t_1 (s)	t_2 (s)	t_3 (s)	t_4 (s)	t_5 (s)	Mean	Range
2	253	158	201	169	187	187.6	253 – 158 = 95
50	69	85	70	91	75	78	91 – 69 = 22

To determine the range for values in Table 1.7.1, you would subtract the smallest value from the largest value. Notice how an abnormally large or abnormally small value in the data set makes the variability appear high. If one value appears way out of range, such as the time taken to reach thermal equilibrium the first time the experiment was performed at 20°C, it may be an outlier. This illustrates the importance of observation during experiments and recording all details in a journal as experimentation and research is conducted.

The experiment was conducted with a smaller number of measurements taken at each temperature, and the results seen in Table 1.7.2.

TABLE 1.7.2 Time to reach thermal equilibrium for an aluminium block and 200 mL water initially at 20°C and 50°C

Temperature (°C)	t_1 (s)	t_2 (s)	t_3 (s)	Mean	Range
20	253	158	201	194	253 – 158 = 95
50	69	85	70	75	85 – 69 = 16

Even though the range has not changed much between Tables 1.7.1 and 1.7.2, the results at 20°C seem more random. In Table 1.7.2 at 50°C, the second reaction could be an outlier as the other two results show excellent agreement. The range simply outlines the total variation in measured results; no other analysis or interpretation can be achieved.

A larger **sample size** will strengthen the **validity** of the range

Measures of central tendency

Measures of central tendency (also called central location) are single values that allow you to describe the central position in a set of data. The mean, median and mode are all measures of central tendency. In Physics, the mean is most common. When a data table includes an 'average' column, the measure of central tendency being used will be the mean.

Consider the following data set: 3, 5, 7, 8, 8, 8, 10.

- The **mean** (or average) is the sum of the values divided by the number of values, which in this case is $(3 + 5 + 7 + 8 + 8 + 8 + 10) \div 7 = 7$.

$$\text{mean} = \frac{\Sigma(x_1 + x_2 + x_3 + \ldots)}{n}$$

where

Σ = sum of

$x_1 + x_2 + x_3$ = measurement$_1$ + measurement$_2$ + measurement$_3$

n = total number of measurements

- The **median** is the 'middle' value in an ordered list of values, which in this case is the fourth value, which is 8.
- The **mode** is the value that occurs most often in a list of values, which in this case is 8. This measure is particularly useful for describing qualitative or discrete data.

The appropriate measure of central tendency to use depends on the type of data you are working with (Table 1.7.3).

TABLE 1.7.3 When to use the different measures of central tendency

Type of data	Mean	Median	Mode
nominal (qualitative)	✓	✗	✗
ordinal (qualitative)	✓	✓	maybe
discrete or continuous (quantitative)	✓	✓	✓

Graphically representing the data using central tendency provides a clear and succinct display of results. As there are many measured values and results in raw data, it can be difficult to analyse and interpret. It is much easier and less complicated to analyse and interpret processed data compared to raw data. Raw data includes all the measured results and usually a large number of measurements or observations.

Processed evidence is usually a smaller number of results that represent all the measured raw data; these representative results are calculated using statistical methods such as mean, median and mode. Therefore, an analysis can be conducted to compare results using three results (e.g. three means) rather than nine results (e.g. nine individual measurements in the raw data). Interpreting a relationship is also much easier and less complicated when using fewer numbers.

It is important to realise that statistical calculations do not produce the true value, but rather a single value (or smaller number of values) that is meant to represent many.

REGRESSION

Regression is the term used to state that the independent variable causes the result in the dependent variable during a scientific investigation. Some relationships between variables are causal, meaning that there is a cause-and-effect relationship. The independent variable is the cause, and the change dependent variable is the effect.

There are numerous statistical calculations that estimate the causal relationship between variables; some calculations provide a value that indicates how directly an independent variable causes the dependent variable result. This attempts to show the strength of the relationship, and to identify if the change in the dependent variable is entirely due to the independent variable.

In physics, not all relationships are direct or straightforward cause and effect. Often there are many variables that influence the dependent variable, and it is helpful to try and predict how much of an effect the independent has on the dependent, while other variables are also influential.

Coefficient of determination (R^2)

The **coefficient of determination** (R^2) can calculate a value that indicates the predictability between the variables based on how much the results vary. The coefficient of determination produces a value that is an estimate as to how well you can predict the dependent variable based on the independent variable, considering the variations in the results. In the examples in Figure 1.7.1, the data of technique 1 does not follow the linear trend line exactly and therefore as the concentration changes (the independent variable), the absorbance (dependent variable) does not always change consistently. Sometimes it changes by 5, sometimes by 2 or even by 10 or more. The coefficient of determination (R^2) is a calculation that considers the variation in the results to estimate the predictability.

For example, a group of students has used two different methods of recording the time taken for an object to roll down inclined planes at different angles (Figure 1.7.1). Method a used a stopwatch while method b used light gates.

Based on the lines of best fit and R^2 values, the second method was chosen to record the data for the experiment.

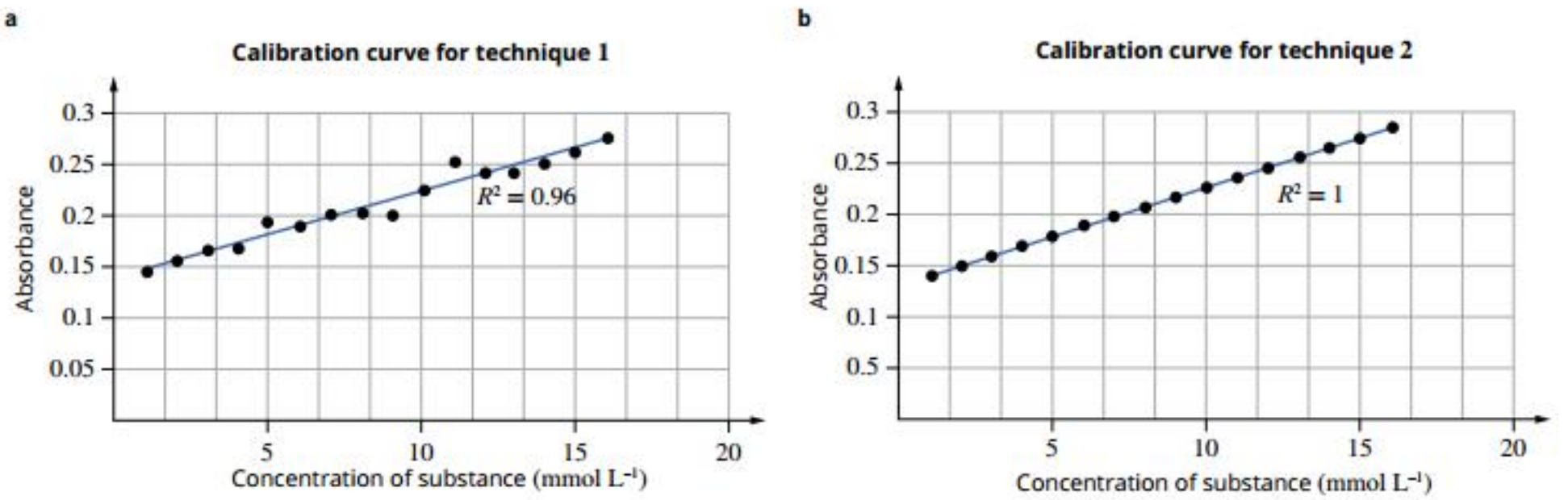


FIGURE 1.7.1 (a) Experimental data recorded with a stopwatch: linear regression was used to establish a line of best fit. (b) Experimental data recorded with light gates: linear regression was used to establish a line of best fit.

Even though both techniques measured the same experiment, the data is different. As can be seen in the graphs, the linear trend line is very similar with a similar slope; however, technique 1 has an R^2 value of 0.96 and technique 2 is 1.00.

The coefficient of determination produces a value between 0 and 1. If the value is 0, it is unable to predict the change in the dependent variable from the independent variable due to so much variation in the results. If the value is 1, then it can predict the change in the dependent variable 100% of the time without error. Any other number between 0 and 1 is considered a percentage, for example 0.76 means that the coefficient of determination can predict 76% of the dependent variable results due to the independent variable. It is interpreted as 76% of the variation in the dependent variable can be explained by the independent variable.

In Figure 1.7.1b, the time is perfectly correlated to the angle without error. This suggests that the results from this method, including error, **bias** and instrumental precision, are highly reliable.

Figure 1.7.1a shows that the time was not precisely correlated with angle. The R^2 value for this method is slightly lower meaning the results are less predictable due to more variation. This method is less precise compared therefore the use of light gates was the preferred technique to collect experimental data in this case.

LINEARISING DATA

A linear relationship is easy to analyse when processing raw data. The *y*-intercept and constant gradient are both readily calculated, and the values often represent physical quantities. For example, the gradient of a graph of force against acceleration gives us the mass of the object from $F = ma$.

So, what happens if your raw data graph is *not* a straight line?

There are ways of processing the curved raw data to obtain values of constants, but they are not easy. A way around this is to convert the raw data into straight-line data via a process called linearisation.

Linearisation involves changing what is graphed along the horizontal and/or vertical axes so that a linear graph is produced. Note that this process does not alter the raw data in any way; it just changes how it is displayed as a graph and is a legitimate way of processing data.

For example, in an experiment the vertical displacement of a dropped rock was measured at various times from an initial height of 24.0 m. The data is shown below in Table 1.7.4 and is used to find a value for the acceleration due to gravity, *g*. Note that uncertainties were recorded but have been removed for this first example.

TABLE 1.7.4 Raw data of the height above the ground of a dropped rock at various times

Time (s)	Height above ground or displacement (m)
0.0	24.0
0.5	22.5
1.0	18.9
1.5	13.9
2.0	5.9
2.3	0.0

A graph of the raw data, with time on the *x*-axis and displacement on the *y*-axis, shows a parabolic relationship (Figure 1.7.2).

As this graph is not linear, it is not immediately apparent how to obtain information about the acceleration due to Earth's gravity. To analyse this data, the graph needs to be linearised to produce a straight line. The data 'looks' parabolic and this is backed up by the quadratic equation that relates the vertical displacement, *s*, of a falling object under Earth's gravity, *g*, over time, *t*.

Linear graphs are the easiest to analyse in physics as they have a y-intercept and a constant gradient.

If raw data does not show a linear trend, the data can be linearised. This involves modification of what is displayed along the independent and dependent axes to show a linear trend.

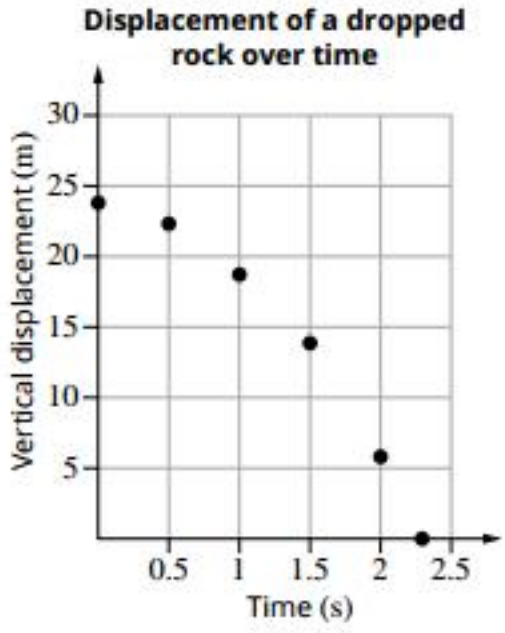


FIGURE 1.7.2 The graph shows a parabolic relationship between vertical displacement of an object falling under Earth's gravity and time.

This is a parabolic relationship between s and t because the independent variable, t, is squared.

To linearise this equation, you transform it into the straight-line equation $y = mx + c$, as shown in Figure 1.7.3. You then match the variables s to y and t^2 to x (shown in blue). You can see the gradient and y-intercept of the linearised t^2 graph (shown in red).

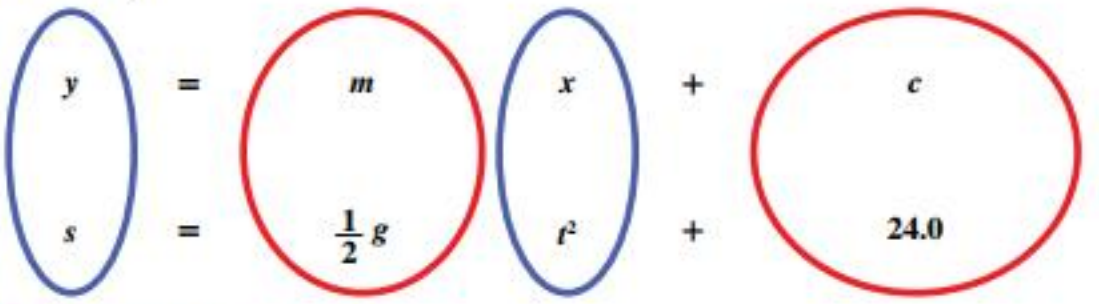


FIGURE 1.7.3 Linearising an equation

To linearise the quadratic equation $s = \frac{1}{2}gt^2 + 24.0$, you equate it to the general equation of a straight line $y = mx + c$:

s is plotted on the y-axis.

t^2 is plotted on the x-axis.

The gradient is $m = \frac{1}{2}g$.

The y-intercept is $c = 24.0$.

For the linearised version of the data, s is still on the y-axis, but the x-axis will now be t^2 rather than t. Time is squared, so insert a new column in the table of data. The y-intercept is the displacement when t is zero. From the table you can see that y-intercept is 24.0 m.

Note that in Table 1.7.5, the time^2 column is inserted immediately to the right of the original time data and that the unit of time is also squared. No change has been made to the displacement column.

TABLE 1.7.5 Processed data including time^2 to be used for the linearised version of the relationship between displacement and time

Time (s)	Time^2 (s^2)	Height above ground or displacement (m)
0.0	0.00	24.0
0.5	0.25	22.5
1.0	1.00	18.9
1.5	2.25	13.9
2.0	4.00	5.9
2.3	5.29	0.0

A graph of displacement versus time^2 should now be a straight line. Figure 1.7.4 shows this as a very good linear fit to the data (R^2 of 0.9994). The linear trend line is also shown.

From the trend line, the gradient is $-4.4744\,\text{m s}^{-2}$, and y-intercept is 23.738 m.

The y-intercept value of 23.738 m is close to the actual y-intercept of 24.0 m, so it is an accurate result.

The gradient value of $-4.744\,\text{m s}^{-2}$ is much lower than the expected value of the acceleration due to Earth's gravity, g, which is $-9.80\,\text{m s}^{-2}$, so what went wrong? Remember (from Figure 1.7.4) that:

$$\text{gradient} = \frac{1}{2}g$$

$$\therefore g = \text{gradient} \times 2$$

$$g = -4.4744 \times 2$$

$$= -8.9488\,\text{m s}^{-2}$$

This value is still slightly inaccurate but that is probably due to air resistance encountered by the falling rock.

This example showed that from non-linear raw data, a linear trend line could be used to find the values of the gradient and y-intercept.

Note that you can only linearise data if there is a relationship between the x- and y-variables in the first place, otherwise the linearisation process is meaningless. Figure 1.7.5 shows that linearisation is not possible if there is no relationship between the variables.

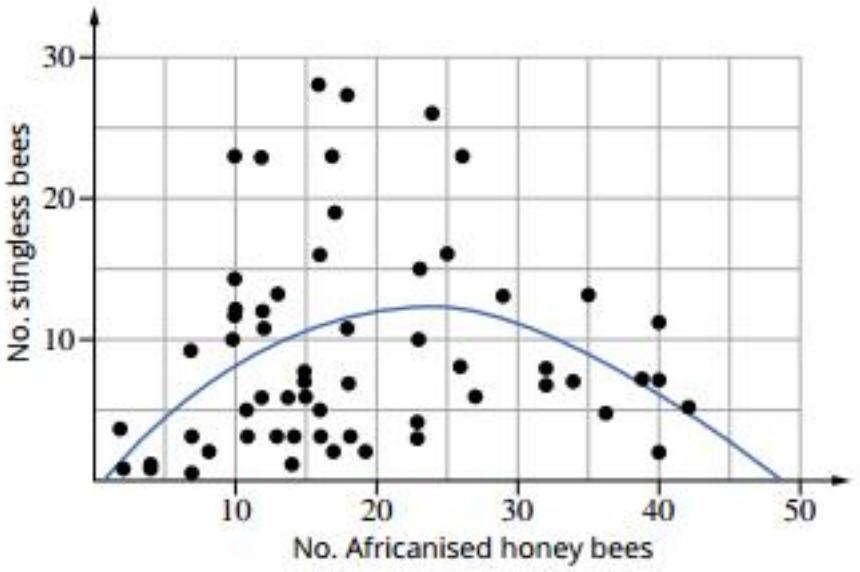


FIGURE 1.7.5 An extremely poor best fit line to the data that was published in the journal *Science* in 1978.

Sometimes the relationship between the x- and y-variables is known, but often it is unknown. This is what makes data analysis in physics exciting: using data and uncertainties to find an otherwise hidden relationship between the dependent and independent variables.

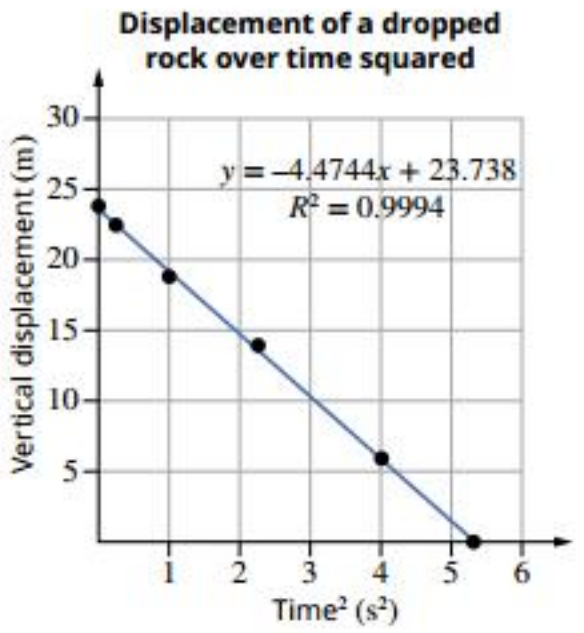


FIGURE 1.7.4 The linearised graph of vertical displacement against time^2, allowing the gradient and y-intercept to be used to calculate the acceleration due to Earth's gravity.

Worked example 1.7.1

LINEARISING DATA

Below are two formulas used in physics. Descriptions of the shapes of the graphs when the raw data is graphed are given in brackets. Assume that all other symbols are constant. For each formula:

i state the variable that would need to be graphed on each of the horizontal and vertical axes of a graph to linearise these equations

ii state the values of the gradient and y-intercept.

a $E_k = \frac{m}{2}v^2$ (E_k on the y-axis and v on the x-axis produce a parabola.)

Thinking	Working
i v is on the x-axis and the graph is a parabola, so the new x-axis variable will be v^2. The y-axis variable, E_k, will not be modified.	New x-axis variable = v^2 New y-axis variable = E_k (unchanged)
ii $E_k = \frac{1}{2}mv^2 + 0$ The y-intercept is zero. The coefficient of v^2 is $\frac{m}{2}$.	y-intercept = 0 gradient = $\frac{m}{2}$

b $F = \frac{GmM}{r^2}$ (F on the y-axis and r on the x-axis produce a hyperbola.)

Thinking	Working
i r is on the x-axis and the graph is a hyperbola, so the new x-axis variable will be $\frac{1}{r^2}$. The y-axis variable, F, will not be modified. Note that technically a hyperbola is proportional to $\frac{1}{r}$, but the general shape and linearisation process is the same for $\frac{1}{r^2}$, $\frac{1}{r^3}$, etc.	New x-axis variable = $\frac{1}{r^2}$ New y-axis variable = F (unchanged)
ii $F = GmM\left(\frac{1}{r^2}\right) + 0$ The y-intercept is zero. The coefficient of $\frac{1}{r^2}$ is GmM.	y-intercept = 0 gradient = GmM

➤ Try yourself 1.7.1

LINEARISING DATA

Below are two formulas used in physics. Descriptions of the shapes of the graphs of the raw data are given in brackets. Assume that all other symbols are constant.

i State the variable that would need to be graphed on each of the horizontal and vertical axes of a graph to linearise these equations.

ii For each formula, state the values of the gradient and y-intercept.

a $T = 2\pi\sqrt{\frac{L}{g}}$ (T on the y-axis and L on the x-axis produce a square root graph.)

b $\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$ (d_i on the y-axis and d_o on the x-axis produce a hyperbola.)

Table 1.7.6 summarises the commonly encountered relationships in physics and shows how to linearise each equation. Note that you will not be expected to linearise periodic relationships.

TABLE 1.7.6 A summary of common relationships in physics, and how to linearise the raw data to produce a straight line. Note that for parabolic, inverse and square root relationships there is more than one way to linearise the raw data.

Graph type	Basic equation	New *x*-axis	New *y*-axis	New gradient
directly proportional	$y = mx$	already linear	already linear	no change
linear	$y = mx + c$	already linear	already linear	no change
parabolic	$y = kx^2$	x^2	no change	k
		x	$\sqrt{y}$	$\sqrt{k}$
inverse (hyperbolic)	$y = \frac{k}{x}$	$\frac{1}{x}$	no change	k
		x	$\frac{1}{y}$	$\frac{1}{k}$
inverse square	$y = \frac{k}{x^2}$	$\frac{1}{x^2}$	no change	k
		x^2	$\frac{1}{y}$	$\frac{1}{k}$
exponential	$y = A\,e^{-kx}$	x	ln y	$-k$
square root	$y = k\sqrt{x}$	$\sqrt{x}$	no change	k
		x	y^2	k^2

THREE-LINE GRAPHS

Any graph showing the relationship between two variables should also include uncertainties as error bars. When raw or processed data yields a straight line, the uncertainties can be used to determine the uncertainty in the gradient and *y*-intercept of the line of best fit. This is done via the use of the lines of maximum gradient and minimum gradient in addition to the line of best fit.

- The maximum gradient line is found by lining up a straight line such that it passes through all of the error boxes (at least part of either the error bars for *y* or *x* of every data point) at the steepest possible gradient.
- The minimum gradient line is found by lining up a straight line such that it passes through all of the error boxes at the shallowest possible gradient.

Note that this can be tedious to do by hand and software is available that will do this automatically.

Figure 1.7.6 shows an example of a linear graph, the best fit trend line and the maximum and minimum lines.

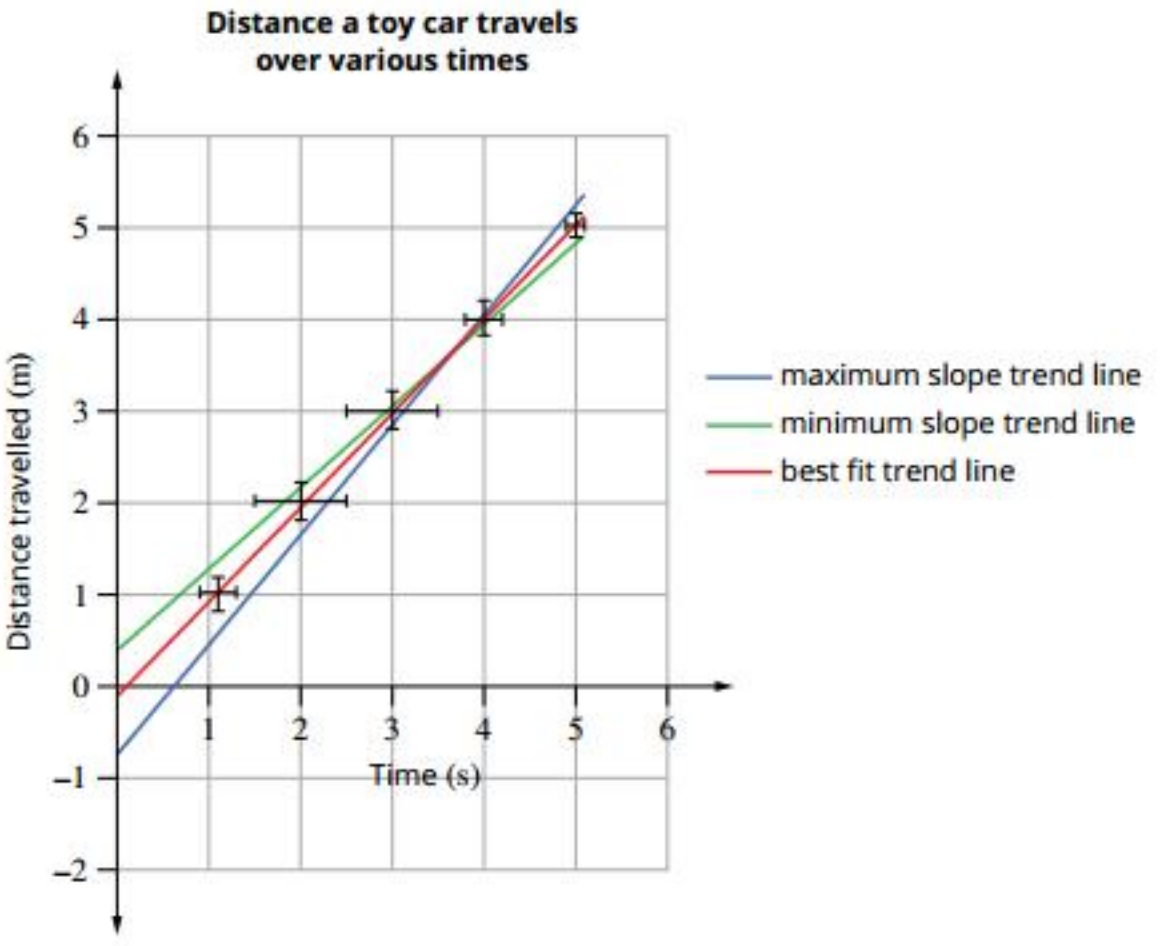


FIGURE 1.7.6 An example of a linear graph showing the best fit line, error bars, and maximum and minimum lines. The minimum and maximum lines are used to determine the uncertainty in the gradient and y-intercept.

If calculations are to be done manually, determine the values of the three slopes (line of best fit, maximum line and minimum line) by choosing two points on each line, not the data points. The y-intercept of each of the three lines can be read off the y-axis. Remember to also include units in your calculations.

If the gradient and y-intercepts are done automatically, they can be read off from the equations of the lines generated by the software. In Figure 1.7.6, the three equations are:

Equation of best fit line: $y = 1.02x - 0.0803$
Equation of the maximum line: $y = 1.19x - 0.753$
Equation of the minimum line: $y = 0.881x - 0.407$

Maximum and minimum gradient lines show the uncertainty in the gradient and y-intercept in linear data.

These data tell us that the difference between the maximum and minimum gradients, and maximum and minimum y-intercepts, are not very large, so the data is quite precise. The line of best fit also lies between the maximum and minimum lines.

Using the same procedure for calculating the absolute uncertainty of the mean on page e41, the uncertainty of the gradient can be found by using:

$$\Delta\text{gradient} = \frac{\text{maximum gradient} - \text{minimum gradient}}{2}$$

And, similarly, the uncertainty in the y-intercept can be fund using:

$$\Delta(y\text{-intercept}) = \frac{\text{maximum } y\text{-intercept} - \text{minimum } y\text{-intercept}}{2}$$

Using the data from Figure 1.6.19, the uncertainties of the gradient and y-intercept are:

$$\Delta\text{gradient} = \frac{1.19 - 0.881}{2}$$
$$= 0.1545\,\text{m s}^{-1}$$
$$= 0.15\,\text{m s}^{-1}$$

$$\Delta(y\text{-intercept}) = \frac{0.407 - 0.753}{2}$$
$$= 0.58\,\text{m}$$
$$= 0.6\,\text{m}$$

Finally, using the correct significant figures and decimal places of uncertainties, the final values of the gradient and y-intercept are:

gradient = $1.02 \pm 0.15\,\text{m s}^{-1}$

y-intercept = $-0.08 \pm 0.6\,\text{m}$.

Note that in this example:

- the gradient represents speed (Distance traveled/time = m/s). The toy car is travelling at a constant speed of $1.02 \pm 0.15\,\text{m s}^{-1}$.
- the y-intercept represents the initial distance travelled. This is expected to be zero, because at time zero the toy car is at the start. The value of the y-intercept has a range of values from +0.5 m to −0.7 m, which includes the expected 0 m. This indicates that the data is quite accurate for this variable.

Table 1.7.7 shows data from an experiment in which the masses and volumes of solid copper cubes were measured in order to find the density of copper (with uncertainty).

TABLE 1.7.7 Raw data of the masses and volumes of five different solid copper cubes that will be graphed and used to determine the density of copper and its uncertainty

Volume of copper cube (±5 mL)	Mass of copper cube (±10 g)
1	10
8	70
24	220
53	480
125	1120

This data is now graphed with volume on the x-axis and mass on the y-axis. Each error bar is shown, but the y-axis error bars are very small and difficult to see. Figure 1.7.7 shows the line of best fit as the red dotted line, with the green and purple dotted lines being the maximum and minimum lines respectively. The equations of each line is also shown, along with the R^2 value for the line of best fit.

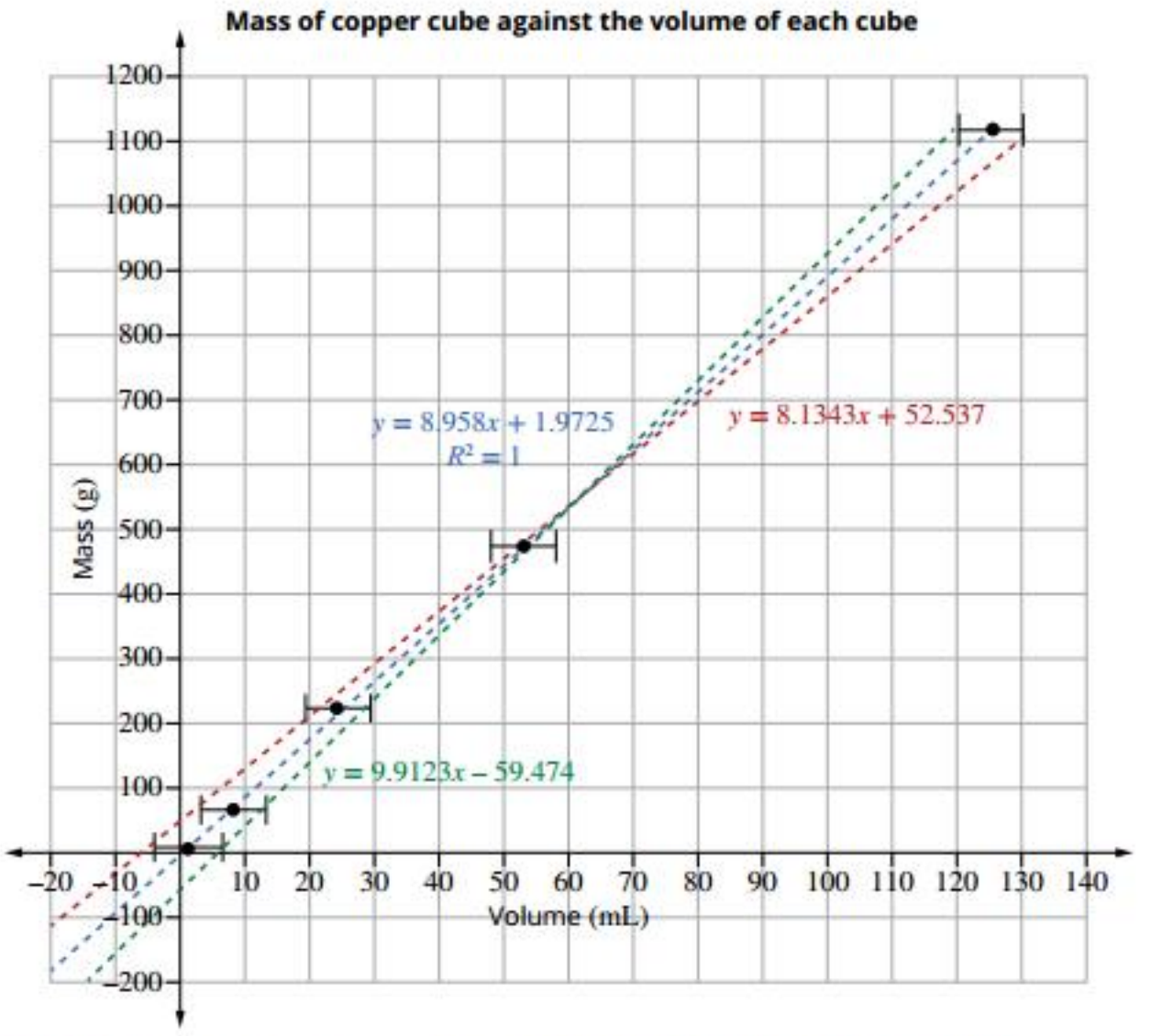


FIGURE 1.7.7 The complete graph, error bars and maximum and minimum lines for mass and volume data of copper cubes. The dots at the extremities of the lines were used to help draw the maximum and minimum lines.

From the line of best fit (red):

$\text{gradient} = 8.958\,\text{g mL}^{-1}$
$y\text{-intercept} = 1.9725\,\text{g}.$

From the graph:

$$\Delta\text{gradient} = \frac{9.9123 - 8.1343}{2} = 0.889\,\text{g mL}^{-1} = \pm 0.9\,\text{g mL}^{-1}$$

$$\Delta(y\text{-intercept}) = \frac{52.537 - -59.474}{2} = 56.006\,\text{g} = \pm 60\,\text{g}$$

Note that in this example:

- the gradient represents the density of copper (mass/volume = g/mL), which is $9.0 \pm 0.9\,\text{g mL}^{-1}$. This is a reasonably precise measurement with a 10% uncertainty, and the discrepancy between this value and the accepted value ($\tilde{n}_{\text{copper}} = 8.96\,\text{g mL}^{-1}$) is only 0.4%.
- the y-intercept represents the mass of a copper cube with zero volume, which is $2 \pm 60\,\text{g}$. You would expect this to be zero because any solid with no volume has no mass. The value of the y-intercept ($2 \pm 60\,\text{g}$) contains the expected value of zero in its range from $-58\,\text{g}$ to $62\,\text{g}$.

The trend line passes through every error bar, so the data is free of outliers and matches theory. The precision of the data can be increased by using a higher resolution balance and callipers to reduce the uncertainty in mass and volume, although it was the uncertainty in volume that was the main source of uncertainty in the calculations. There is no evidence of systematic error because the value of the y-intercept contains the expected value of zero in its range.

Systematic and random errors in graphs

Graphs can reveal systematic and random uncertainties. Systematic errors will reveal themselves on linear graphs if the actual measurements do not match the predicted values, but there is an obvious pattern. Random uncertainties show as error bars, and these can be used to determine the uncertainty in the gradient and y-intercept of the line of best fit.

Incorrectly calibrated equipment will give the type of graph shown in Figure 1.7.8. This type of systematic error comes from an incorrectly scaled instrument.

For example, a ruler that has an incorrectly calibrated scale could read 1.2 cm when it should read 1.0 cm, and read 2.4 cm when it should read 2.0 cm.

Incorrectly zeroed equipment will give the type of graph shown in Figure 1.7.9. All measurements along the y-axis are offset by the same value.

For example, an electronic balance incorrectly zeroed could read 1.4 g when it should read 1.1 g, and 23.7 g when it should read 23.4 g.

Any graph showing the relationship between two variables should also include uncertainties as error bars. When raw or processed data yields a straight line, the uncertainties can be used to determine the uncertainty in the gradient and y-intercept of the line of best fit. This is done via the use of the lines of maximum gradient and minimum gradient as explained earlier in this module.

Systematic errors are seen in graphs when every data point is shifted out of its theoretical position by the same amount or same ratio.

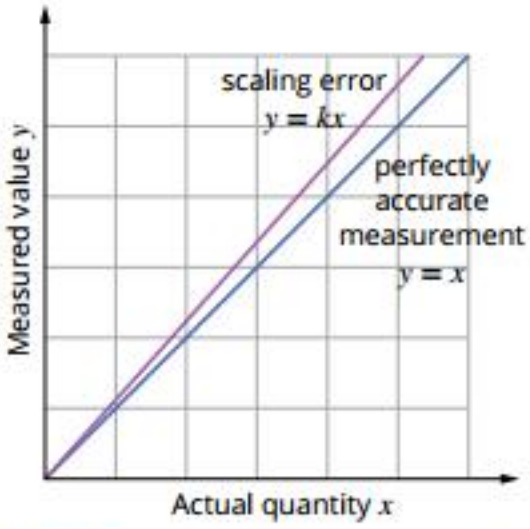


FIGURE 1.7.8 The recorded measurements are k times their real values. This means that the instrument's scale did not match the scale indicated on the display or on the graduated marks.

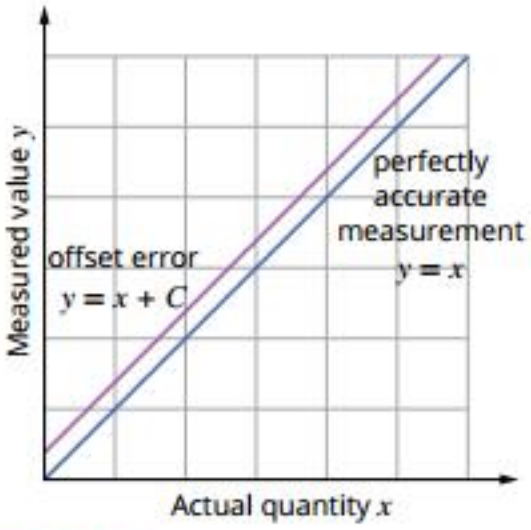


FIGURE 1.7.9 The recorded measurements need to be reduced by C to give the real values. This means that the instrument was not fully reset to zero before measurements were made.

1.7 Review

SUMMARY

- The mean, $\bar{x}$, is the average of a data set. It is calculated using the formula:
  $\bar{x} = \frac{\sum x_1 + x_2 + x_3 \cdots}{n}$, where
  Σ = sum of
  $x_1 + x_2 + x_3$ = measurement$_1$ + measurement$_2$ + measurement$_3$
  n = total number of measurements.
- The median is the 'middle' value in an ordered list of values.
- The mode is the value that occurs most often in a data set.
- Regression is the term used to state that the independent variable causes the result in the dependent variable during an experiment.
- Linear regression is a calculation that estimates a direct linear relationship between the independent and dependent variables.
- The coefficient of determination estimates how well you can predict the dependent variable based on the change in the independent variable.
- The coefficient of determination produces an R^2 value between 0 and 1.
  - The closer R^2 is to 0 the less predictable the dependent result is based on the independent value.
  - The closer the R^2 is to 1 the more predictable the dependent result is based on the independent value.
- Systematic errors appear in graphs where the data for x or y are shifted or multiplied by the same value.
- Commonly used graphs in physics are linear, parabolic (squared), inverse (hyperbolic), inverse square, sine and cosine, and exponential decay curves.
- A linear graph is the easiest to analyse because it is straightforward to calculate the gradient and y-intercept, and these are used in further processing of the data.
- Any graph that is not linear can be linearised to produce a graph that has modified x- and y-axes.
- The minimum and maximum lines are used to calculate the uncertainty in the gradient and y-intercept.

KEY QUESTIONS

Describe

1 Describe the terms 'mean', 'median' and 'mode'.

2 Describe the coefficient of determination

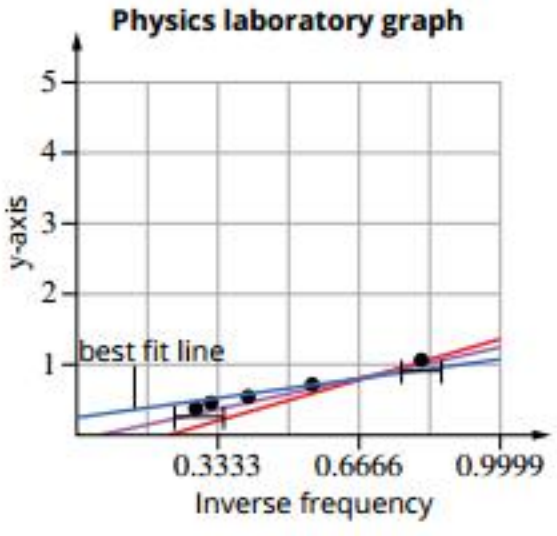
3 Explain why linear graphs are much easier to analyse than curved graphs, such as parabolic or hyperbolic graphs

Apply

4 For the data set {21, 28, 19, 19, 25, 24, 20}, calculate the:

a range
b median
c mode
d mean
e standard deviation

5 Consider the graph shown below.



a List the mistakes or poor techniques in this graph.
b For each mistake in your list, identify how the graph could be corrected or improved.

Analyse

6 Identify which of the statistical measurements of mean, mode and median is generally most affected by an outlier.

7 Melissa draws a straight line graph of data, including error bars, from an experiment she has just completed. She finds that it is not possible to draw a straight line of best fit through every error bar. Explain to Melissa why this is the case and suggest some improvements to her data.

8 If theory suggests that the *y*-intercept of a line is zero, deduce what this should look like on a scatter plot with a line of best fit.

9 Below are two formulas used in physics. A description of the shape of the graph of the raw data is given in brackets. Assume that all other variables are constant.

- **i** Describe what modified variables, if any, need to be plotted on each axis to produce a linear graph.
- **ii** Identify the gradient and *y*-intercept in each case.

a $F = \frac{kq_1q_2}{r^2}$ (F on the *y*-axis and r on the *x*-axis produces an inverse square graph)

b $B = \frac{\mu_0 I}{2\pi r}$ (B on the *y*-axis and I on the *x*-axis produces a straight line.)

10 The resistance, R, of an unknown, constant resistor can be found by using voltage, V, and current, I, data in a circuit. The theoretical relationship between voltage and current is given by $I \propto V$. The results of the experiment are recorded in the table.

Voltage $V \pm 0.5$ V	2.0	4.0	6.0	8.0	10.0
Current $I \pm 0.03$ A	0.19	0.44	0.55	0.68	0.94

a Identify the independent and dependent variables.
b Draw a graph of this data, using suitable axes, scales, labels and error bars.
c Draw the line of best fit.
d Draw the maximum and minimum lines.
e Determine the gradient of the line of best fit, maximum line and minimum line.
f Calculate the value of the resistor and its uncertainty.
g Comment on the value of the *y*-intercept and its uncertainty.

1.8 Scientific writing

The QCAA requires you to complete a student experiment as part of Unit 3 Physics and a research investigation in Unit 4 Physics. In preparation for Units 3 and 4, your teacher may assign similar assessment tasks in Units 1 and 2. Both tasks require written or multimodal presentations. Preparing and presenting scientific reports and investigations involves research and note-taking skills, use of scientific genre, language and representations and referencing knowledge to acknowledge sources used.

Scientists follow strict genre conventions when undertaking and communicating their work. These are described in this module. Refer back to this module as you complete the Student experiment and Research investigation.

SCIENTIFIC WRITING AND REPRESENTATIONS

Scientific reports must be written using scientific language and representations; these should be relevant, fluent and concise. To meet the word count or time requirements, only use the words required to communicate your information, and avoid repetition (Figure 1.8.1). Having a plan and using a journal also helps to achieve fluent and concise writing. Use the syllabus objectives, specifications, and the instrument specific marking guide (ISMG) to plan an outline of each section of your written task.

Table 1.8.1 demonstrates communication of the same concept in a few different ways. Being fluent and concise will significantly influence the word count of the report and the quality of the writing.

TABLE 1.8.1 Communicating concepts in various ways

Concept: the basic structure of an atom	
Communication	**Commentary of communication**
An atom is made up of protons, neutrons and electrons.	This is fluent and concise, but lacks scientific terms or language to convey in-depth understanding.
Atoms are tiny little objects made up of numerous parts that form the basis of matter. Atoms are made up of electrons, neutrons and protons. The electrons are found away from the centre of the atom. The centre of the atom contains the protons and neutrons.	This is fluent, but not concise. There is repetition (e.g. 'tiny' and 'little'—these terms have the same meaning; also 'made up' is stated twice). It also uses many words without using scientific terms to provide detail and understanding. This may be useful language in the journal when learning about a topic, but not in the scientific report.
Atoms are particles composed of three subatomic particles: the proton, electron and neutron. The centre of an atom is the nucleus and contains the protons and neutrons, with the electrons occupying space external to the nucleus.	This is fluent and concise. Repetition is avoided. Much in-depth understanding is communicated through scientific terms, which enable relevant information to be conveyed in fewer words.

Reports are written using paragraphs, with each paragraph explaining only one idea. The first sentence (topic sentence) of the paragraph introduces the topic. Following sentences provide the details of the idea. The final sentence concludes the idea and may also link to the idea of the next paragraph. Each sentence should flow onto the next, slowly building the details of the explanation. Headings and subheadings can be used to structure and break up the report.

Reports should be written using:

- scientific language—the terms used are specific to concepts, models and theories
- information from secondary or tertiary sources which is written in your own words
- objective, unbiased language—avoid subjective and emotional or persuasive writing (Table 1.8.3)
- concise language—avoid unnecessary repetition and express ideas in scientific language. Scientific language allows more details, knowledge and understanding to be communicated in fewer words. Use shorter sentences that are less wordy (Table 1.8.4).

The 'method' part of a report is often written in the past tense as the experiment was conducted in the past.

Reports can be written in first person, active voice, or third person, passive voice (Table 1.8.2). First-person voice can be clearer, but it can put the focus on who is doing the action, whereas third-person voice focuses on the action itself.

Table 1.8.4 shows some examples of more concise wording.

TABLE 1.8.2 Examples of first-person and third-person narrative

First person	Third person
I put 50 g of marble chips in a conical flask and then added 10 mL of 2 M hydrochloric acid.	*First, 50 g of marble chips was weighed into the conical flask and then 10 mL of 2 M hydrochloric acid was added.*
After I observed the reaction, I found that ...	*After the reaction was completed, the results showed ...*
My colleagues and I found ...	*Researchers found ...*

TABLE 1.8.3 Persuasive writing versus scientific writing styles

Persuasive writing examples	Scientific writing equivalent examples
Biased and subjective language: *The results are extremely bad/atrocious/ wonderful etc.* *This is terrible because ...* *This produced a disgusting odour.* *Health crisis!*	Unbiased and objective language: *The results showed ...* *The implications of these results suggest ...* *The results imply ...* *This produced a pungent odour.* *Health issue*
Exaggeration: *The object weighed a colossal amount, like an elephant.*	Non-emotive language: *The object weighed 256 kg.*
Use of everyday or colloquial language: *The bacteria passed away.* *The results don't ...* *The researchers had a sneaking suspicion ...*	Use of formal language: *The bacteria died.* *The results do not ...* *The researchers predicted/hypothesised/ theorised ...*

TABLE 1.8.4 Examples of verbose and concise writing

Verbose writing	Concise writing
Due to the fact that ...	*Because ...*
Smith undertook an investigation into ...	*Smith investigated ...*
It is possible that the cause could be ...	*The cause may be ...*
end result ...	*result ...*
In the event that ...	*If ...*
shorter in length ...	*shorter ...*

To produce a fluent report, the scientific language must be used without error so that the reader understands the meaning of the information easily. Refer to the glossary at the end of the student book or to the subject matter sections of the syllabus for the correct scientific terminology. For the report to be concise, there should not be any repetition. Being fluent and concise will significantly influence the word count and the quality of writing. Refer to the syllabus ISMG to identify the cognitive verbs used in the descriptors to produce the appropriate response. For example, you will need to write more extensively if you are asked to 'discuss' or 'explain' compared to 'identify'.

Scientific representations

Chemical or nuclear structures, equations and diagrams are an efficient way of presenting complex data and explaining concepts. Flow charts, graphs, tables and photographs are also used. Ensure you include:

- a descriptive title
- labels, captions or descriptions
- numbering; for example, Figure 1, Figure 2 etc. or Table 1, Table 2 etc.
- a source if the work is not your own or is adapted from work that is not your own.

SCIENCE JOURNAL

There is a lot of information to record during the student experiment or research investigation so it would be best to keep a **scientific journal**. Entries in your journal should include the following features:

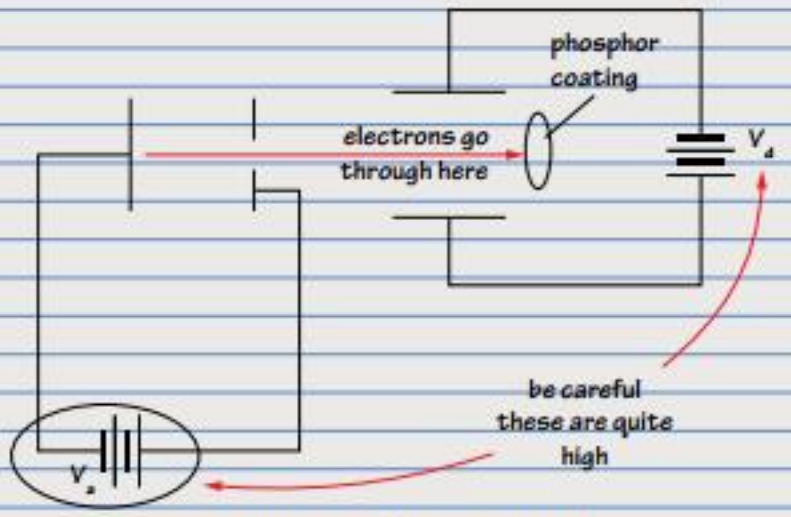
- the date of entry
- ideas, observations, proposals, questions
- background information you researched for the task
- new terms and definitions
- refinements
- results, data, evidence, variables
- explanations, ideas, observations (including diagrams)
- limitations, conclusions, further investigation.

A journal holds a record of information used during the process of the scientific method (Figure 1.8.1). You will not know what is vital information until your experiment is complete and summarised into the scientific report. Data and graphs may be saved digitally so reproduce a sketch in your journal that you can annotate with your thoughts. You may choose to prepare a page or two each for the four key sections of the task (eg. for IA2: Forming, Finding, Analysing, Interpreting and Evaluating) or use proposed report headings (eg. Rationale, Research Question etc.).

Researched and recorded information in your journal will be used for the Rationale; to justify the modifications to the methodology; to provide a reason for collecting data; to inform risk, ethical and environmental management and to collate and process the data. It will also inform the interpretation of the evidence (results) and conclusion. Remember, parts of the Rationale (planning) and the data collection may be completed with your group and shared; the rest of the task is individual and so is your journal. A journal is not an assessed part of the task but will likely be reviewed by your teacher as a progress check and to confirm that the work is yours. Depending on the size of the journal, it may be copied and attached in the Appendix of your report.

12.8.18

Apparatus set up for e/m movement



Switch polarity? To do tomorrow!

1) Record V_a + calculate velocity

2) Measure V_d + calculate ~~electric~~ magnetic field, B

V_a	v	V_d	B
1000		1100	
2000		1100	
3000		1200	
4000		1200	

Not enough variation!

Try new V_a values!

FIGURE 1.8.1 A journal entry with the journal entry date, titles and apparatus used in preparation for an experiment. There will be numerous journal entries on any given date, and they should have their own titles. Also, the same titles will appear on different entry dates as research continues on specific topics.

Journal entries can take different formats. Sometimes one form of recording information provides more details than others. Note taking is not limited to words. Figure 1.8.2 presents the same information in different ways.

a

Newton's law of universal gravitation states that every mass in the universe attracts every other mass.

b

Newton's Law of Universal Gravitation:

$$F = \frac{Gm_1m_2}{d^2}$$

m_1 = mass of planet
m_2 = mass of Sun
d = distance between them

force on planet from Sun
=
force on Sun from planet
∴ small planets must exert a pull on the Sun!

c

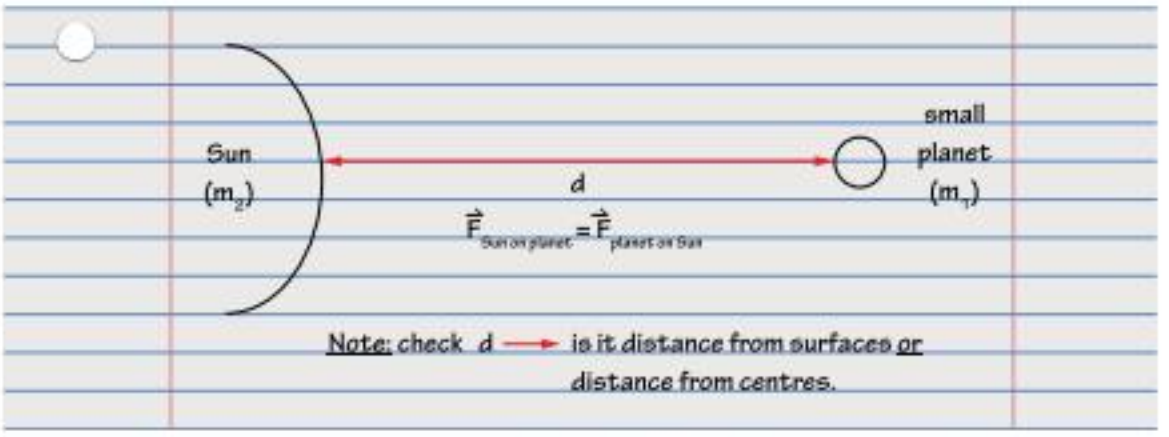
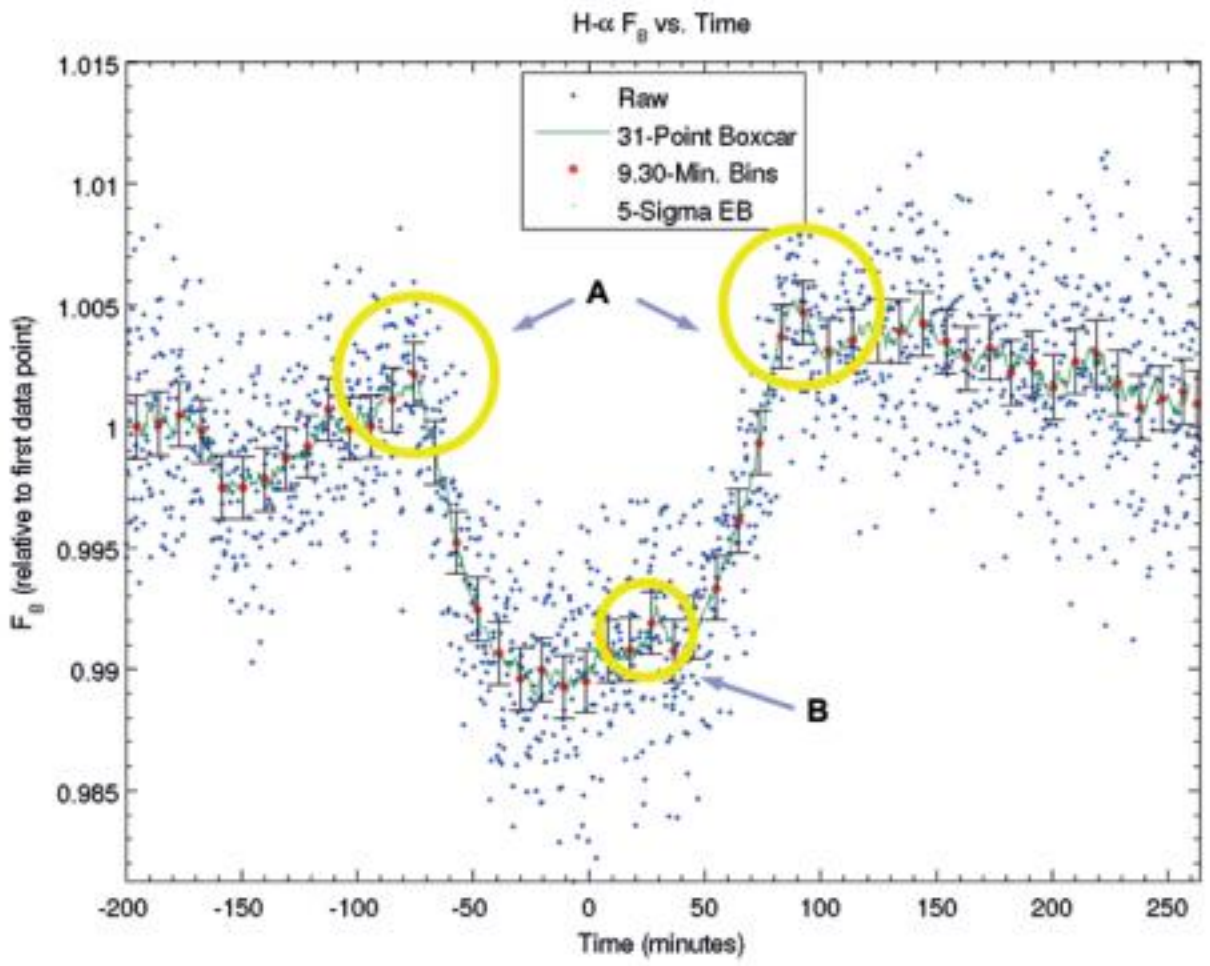


FIGURE 1.8.2 Sample page from a journal explaining Newton's law of universal gravitation (a) in the claim that small planets exert a pull on the Sun, (b) in a flow chart as a schematic to unpack the above claim, and (c) in a diagram

When recording results, data or evidence in your journal, be critical and interpret the data as it is collected. In this way, errors in the method are identified, or sample size can be adjusted, if needed. If a given group member has the recording task, it is vital that the dataset is passed to all group members before leaving the laboratory. Add this information directly into your journal and annotate with your own comments. Figure 1.8.3 shows examples of research evidence and how they can be reinterpreted for a journal entry. Figure 1.8.3a is the original evidence the student found through research and Figure 1.8.3b is the student's notes and interpretation of the evidence. Notes in your journal can also include:

- specific details and your interpretation of significant values
- the trend or pattern, and a statement of whether this is the expected one
- the comparison or difference between one set of values and another
- the statistics used to establish the significance and the author's interpretation.

a



b

21-8-17

This is the light curve -> F_B (flux or intensity) of the star DS16402 over 7½ hours, in hydrogen-alpha or 656 nm wavelength.

The features are : a big dip from −80 minutes to +50 minutes

: the brightness (?) appears to be larger after the planet had passed than before it passed (marked as "A")

: There is a smaller dip at about −150 minutes -> not sure why or if it is important.

http://user.astro.columbia.edu/~astrobio/Transit_detection.html

Statistics and Analysis

Red dots = averaged data over 9½ minutes with error bars ✓

Blue dots = raw data ✓ (no error bars?)

Box car = ?

22-8-2017

Box car = A method of smoothing data recorded over a time interval. e.g. over 31 samples in this example

http://sunnytek.net/admin/xiazaifiles/2010114103920522.pdf

FIGURE 1.8.3 (a) An example of original evidence found during research. (b) An example of a student record of their interpretation of the evidence found in the resource.

REFERENCING SOURCES

When gathering scientific evidence for a scientific inquiry such as Student Experiment and Research Investigation, source it from reputable publications such as:

- your textbook and practical manual. This should be your first source of reliable information.
- scientific journals and magazines: research papers and scientific reviews. Common commercial science magazines that you might find in your school library include *Double Helix*, *Cosmos*, *Scientific American* and *New Scientist*. Scientific journals are peer-reviewed which gives them credibility.

- podcasts and websites. Electronic sources include online scientific organisations such as CSIRO, NCBI, AIMS, Bioscience (Oxford Academic) and other university publications and press. In general, use websites that are .edu, .gov or .org. Many government and privately funded science organisations publish material, along with not-for-profit scientific organisations. Websites may direct you to magazines and scientific journals, podcasts, blogs and videos.

In the syllabus, you are asked to "discuss and evaluate the validity and reliability of evidence" (Science Inquiry skills). When selecting and using sources of information and evidence, follow these guidelines:

1 Confirm that it is relevant.
   - **a** Check that it contains information that is specifically related to the inquiry
   - **b** Check that the evidence and information are pertinent to the variables of the inquiry.
2 Assess its reliability.
   - **a** Is it current/recent information?
   - **b** Is it correct in its understanding of relationships?
   - **c** Is the evidence in agreement with other sources?
   - **d** Check credibility and bias — consider who the author is, their qualifications, expertise and possible affiliations.
   - **e** Evaluate the methodology, including what variables were controlled or measured.

It is not necessary that each of your sources fulfill all of these requirements. Each source will have strong and weak points. For example, we are confident that information from a peer-reviewed scientific journal is unlikely to lack credibility or contain bias because the review process is undertaken by experts in the field. However, it may have been produced 10 years ago and so scientific information and relationships may not be up to date. Also, podcasts or science magazines for school students may contain a wide array of interesting real-world examples but not explain the scientific understandings in sufficient detail. An informed discussion of these types of issues is part of the evaluating section of the Research Investigation. Some resources are available by paid subscription, so use advice from your school librarian about free resources or join your local library.

All quotations, documents, publications and ideas used in your investigation need to be acknowledged in the reference list in order to avoid plagiarism and to ensure creators are properly credited for their work. When using sources to explain concepts or review data, ideas must be written in your own words (see plagiarism, below). References and acknowledgements show that you have read widely, give credibility to your study and allow the reader to locate information sources should they wish to study it further.

Plagiarism

Plagiarism is using other people's work without acknowledging them as the author or creator. To avoid plagiarism, include a reference every time you report the work of others, for example, at the end of a sentence or following a diagram. If you use a direct quotation from a source, enclose it in quotation marks. This will ensure you give credit to the original author and it will enable the reader to find the original source.

Information taken from a source should be rewritten in your own words. It can be difficult to reword information in your own words. A useful strategy is to read the information, understand it, then, without looking back at the source, take notes in your journal. Notes that are detailed and have full explanations will be useful when you refer to them later to write the report.

TABLE 1.8.5 Suggestions for rewording information.

Source information:
"It can be expected that the days will be warm and the nights will be cool over the next three days due to the high pressure system moving across the region."

Strategy to change source information	Reworded information
The order of information can be swapped- the object (the warm days and cool nights) with the reason (high pressure system).	Due to the high-pressure system moving across the region, the days will be warm and the nights will be cool.
Some words can be changed such as adverbs, nouns, verbs, adjectives.	It has been predicted that during the daytime it will be warm while the evenings will be cool for about three days, as a high-pressure system travels over the region.
Information can be elaborated to explicitly outline information.	The weather forecast expects (or, made a prediction based on computer simulations) that the temperature during the day will be warm (22-25°C) and the evenings will be cool (below 12°C) due the high-pressure system (or, weak high-pressure system), which dissipates clouds and allows direct sunshine to warm Earth's surface; however, in the evenings this system brings cool air from higher altitudes, which is no longer warmed by the sun.

Referencing

There are several different referencing styles, such as Harvard or APA. The sources of information must be acknowledged using a referencing style that is suitable for the purpose of the investigation. Check the preferred referencing style or convention of your teacher for in-text referencing and a complete a **reference list**. APA (American Psychological Association) style is the most commonly used referencing style.

A bibliography is a list of all the sources used during the research to develop understanding (including information in the journal) even if the information was not used directly or explicitly in the scientific report. A reference list only lists the sources used and cited (or in-text referenced) in the scientific report. As such, a reference list is the minimum requirement and you may choose to extend this to a bibliography. The sources must be listed at the end of the report in the style consistent with your style of referencing.

Compile all references you use both directly in the scientific report or in the gathering and development of the information in a separate document as you conduct the investigation. This will save you time later. Microsoft Word, and other online tools make writing a reference list easier by automatically formatting references in the referencing style of your choice. Always check that this tool has formatted correctly.

In-text citations

Each time you write about the findings of other people or organisations, you need to provide an in-text citation and provide full details of the source in a reference list. The Vancouver style of referencing uses sequential numbering of the references, which are either stated [1, 2 ...] etc or as subscripts after the information that is being referenced. Each individual work by the same author, even if it is published in the same year, has its own reference number. Whereas, Harvard and APA style, in-text citations include the first author's last name and date in brackets (author, date).

The following examples show the use of in-text citation and the corresponding reference list entry for an article in a journal in APA style. The format varies slightly according to the type of document or source you are referencing. Useful guides can be found online including many university websites.

TABLE 1.8.6 Example used of in-text citation.

Source of information and example of reference in text	Format for listing references and example of a reference as written in the reference list
Research article or review article in a scientific journal A single atom of the rare-earth metal holmium has been made into the world's smallest, stable magnet. This was then used to make an atomic hard drive, in which each holmium atom stored one bit of information (Natterer et al., 2017).	Author, initials. (year). Title of article. Journal title, volume number (issue number), page numbers. Digital object identifier (doi) or URL Natterer, F., Yang, K., Paul, W., Willke, P., Choi, T., Greber, T., Heinrich, A., & Lutz, C. (2017). Reading and writing single-atom magnets. Nature, 543, 226–228.
Book Hawking (1988) discusses the theories of general relativity and quantum mechanics and seeks to describe a unifying theory that combines these.	Author, initials. (year). Title of book (edition, if not first). Publisher Hawking, S., (1988). A brief history of time: From the big bang to black holes. Bantam Books.
Online article or page A layered crystal (created with hafnium oxide and zirconium oxide) reduces the required voltage by around 30% (Perfetto, 2017).	Author, initials/name of organisation. (year). Title of webpage or web document. URL Perfetto, I., (2022, April 1). New crystal could help transistors run on less power. Cosmosmagazine.com. https://cosmosmagazine.com/technology/ computing/crystal-for-transistors/

USING AI IN RESEARCH AND WRITING

Generative AI (or just AI) uses chatbots or digital assistants that you can communicate with using fairly natural language to access information in Large Language Models (computer models trained on vast amounts of data). These typically generate text, and some models can generate images, video and audio.

AI can be great for brainstorming ideas about investigations, generating practice questions and generating data for investigations. However, you must follow guidance from your teacher or school on how you can use AI in your work. You could be penalised by your school for using AI-generated material without permission or acknowledgement. It's also important to understand the limitations of AI-generated text.

Check with your teacher before using AI in your work.

Acknowledge use of AI using referencing conventions.

Always fact check AI-generated text and references.

Limitations of AI-generated text

Large language models are engineered to match patterns of words, but they cannot understand the meaning of your prompt or the output text. They produce text that is similar to patterns of words in the prompts and outputs they have been trained on.

This can result in text that sounds knowledgeable and authoritative but does not mean much when you examine it or try to rephrase it in simple language. AI can hallucinate – i.e. make up statements – and this can be obvious or subtle. For example, AI can give correct answers to questions it has generated but give the wrong explanations.

The data that the model is trained on is not necessarily scientifically accurate, so generated text could be incorrect or biased. AI can be prompted to provide references, but these are often not reliable.

AI-generated answers may not model the complete response that aligns with the scope and scale of the syllabus. In class, you will have developed an understanding of the scientific concepts described in the syllabus. In this way you can check the level of information and accuracy provided in an AI-generated response.

Referencing AI sources

You must properly acknowledge the use of AI in your work. Some AI tools provide a URL that will link to generated text. If yours does not, it's a good idea to include the prompt you used and the AI output as an appendix to your work. The following are sample ways to reference AI-generated text (Table 1.8.7).

TABLE 1.8.7 Examples of ways to reference AI-generated text.

Referencing style	General format	Example
APA	Author. (Year). Title of software program (Version). Date. URL. Appendix.	OpenAI. (2024). *ChatGPT* (20 June version) [Large multimodal model] https://chat.openai.com/chat or 'see Appendix for prompt used and output generated'.
Chicago	Footnote number. AI tool used, Month Day, Year, Creator of tool, URL, Appendix.	1. Text generated using GPT-4o, June 20, 2024, OpenAI, URL or 'see Appendix for prompt used and output generated'.

Prompting the digital assistant

Learning to write effective prompts is essential to get good results from AI. There is no perfect way to write a prompt, but using one of the many frameworks can be useful. Keep the instructions simple – for example:

- Role (Who the chat assistant is being: e.g. policy maker, marketer, consumer)
- Task (What output you would like: e.g. an article, summary, set of questions)
- Format (What it should look like: e.g. bulleted list, table, graph)

For example: I am a government policy maker working on energy strategy. Give me a one-page summary of pros and cons of using nuclear power in Australia. Consider cost, climate change, security, the environment and First Nations' perspectives in your answer. Present the summary in bullet points and include accurate references for all data.

If necessary, you can refine the results using further prompts. Note that chat assistants are not predictable, and you can get different results using the same prompt.

MULTIMODAL PRESENTATIONS

Student experiments and research investigations are focussed investigations resulting in a conclusion related to the initial question posed. In schools, the process occurs over a number of lessons but in research science a project can continue for weeks, months or years. The reporting of the final findings is usually a written report published in a scientific journal but can also take place at a scientific conference. In the Queensland Physics syllabus, you are also provided this flexibility in the form of a multimodal presentation as an alternative to the written report.

It is important to note that this mode gives you an option for the final presentation of the task only. All criteria and descriptors in the Instrument Specific Marking Guide relating to forming, finding, analysing and interpreting/evaluating need to be met as described in Parts B and C. Multimodal presentations must include at least two modes of delivery at the same time, have a maximum time of 11 minutes and a maximum of 2000 words. Your two modes are likely to be visual (PowerPoint or poster) and verbal (speech). For average speaking speed, 11 minutes will equate to around 1600-1700 words. Your teacher will need the PowerPoint printed and a printed script; they may record your presentation. Another option is to use the audio record function of PowerPoint. These aspects of assessment will be identified by the school on their endorsed task(s).

Some considerations regarding the speech are:

- engage and effectively communicate with the audience
- use a clear structure; it is suggested to follow the outline of a written report (see headings provided in Part B)

- interact with your PowerPoint or poster to point out important aspects
- while it is not advised to speak on a tangent or set up a conversation with the audience, it would be possible to ask the audience if they have any questions
- use a strong confident tone
- bring your own timer to avoid going over time

Some considerations regarding the visual presentation (for PowerPoint):

- each slide should have a clear focus with minimal text (6-7 lines per slide, 6-7 words per line). Use minimum 24 font so that audience can read.
- present a single graph or table per slide. For graph axes or annotations in smaller font you should read this information
- use a consistent design or theme

Some considerations regarding the visual presentation (for poster):

- use a presentation size large enough to include all your graphs. figures and text.
- make the poster 'flow' so the reader clearly follows the investigation from planning through to concluding and evaluating.
- allow your audience some time before the presentation to view the information and allow them to formulate questions.

Communicating experimental or research findings is an integral part of a scientist's work. Irrespective of the time span of the investigation, there is a sense of achievement when the results are made known, especially when the process requires you to relate to the topic in depth. By choosing a verbal presentation, you are able to share this journey with the audience.

1.8 Review

SUMMARY

- Scientific reports use scientific language and representations
- The language of scientific reports is concise, objective and written in the third person
- The scientific visual representations include tables, charts, graphs, tables, illustrations
- Visual representations include headings, labels, captions, descriptions, numbering (if more than one item)
- A science journal is a useful tool for recording detailed information and sources during an investigation
- Write using your own words to avoid plagiarism
- Acknowledge sources and any references to the work of others by including a reference list
- If using AI for scientific research ensure information is checked against other sources, avoid plagiarism and acknowledge the source

KEY QUESTIONS

Describe

1 Explain the difference between a bibliography and a reference list.

2 Describe what plagiarism is and indicate why it is unacceptable.

Apply

3 List the information that should be recorded about an online source in your journal.

4 Explain the benefit of keeping a scientific journal.

Analyse

5 Rewrite the following text in your own words.

a A group of patients was administered adrenaline during a cardiac arrest to determine if adrenaline would improve patient outcomes. There was no statistically significant improvement in patient outcome between patients who received adrenaline and those who did not.

b A team of scientists from the Oregon Health and Science University and Korea's Institute for Basic Science successfully repaired a defective gene in human embryos. The gene that was targeted caused a heart defect, known as hypertrophic cardiomyopathy, which causes sudden death in young adults.

1.9 Syllabus requirements

The student experiment requires you to undertake the full **scientific method**. The Physics General Senior Syllabus 2025 states that this process begins with a practical conducted during class or viewed online. This practical will be modified to conduct your own experiment. It is recommended that during the class practical you record your observations, queries and thoughts as well as collecting and processing data. These notes can be used to lead to a research question or hypothesis for the student experiment. This task assesses syllabus objectives, science inquiry skills and relates to student experiment objectives and specifications from the Physics General Senior Syllabus 2025.

The student experiment constitutes 20% of the total assessment and may be presented in:

- written form (such as scientific report), up to 2000 words, or
- multimodal presentation form (at least two modes delivered at the same time), up to 11 minutes.

In the modules that follow, you will find a guide to a scientific method and an outline for producing a student experiment report.

INSTRUMENT-SPECIFIC MARKING GUIDE

Student responses are assessed against an instrument-specific marking guide (ISMG). In developing your experiment and planning your response, it is important to always have in mind the assessment objectives, and in particular the characteristics that are described in the performance level descriptors.

- The ISMG has four criteria (criterion):
  - forming
  - finding
  - analysing
  - interpreting and evaluating
- Criteria have performance levels, against which the qualities of the response are assessed. The table below shows the high-performance level characteristics for the four criteria.
- A performance level consists of a descriptor and mark or mark range.
- The performance level descriptor describes the characteristics that are demonstrated by a response at this quality.
- The ISMG criteria, and elaborations of each are shown in Table 1.9.1, for the highest performances.

TABLE 1.9.1 Alignment of syllabus criteria, objectives, descriptors and marks with the modules of Part B

Criteria	Assessment objectives	Instrument specific marking guide (ISMG) descriptors – Criteria are demonstrated by:	Marks	Module
Forming	1. Describe ideas and experimental findings about gravity and motion, or electromagnetism. 2. Apply understanding of gravity and motion, or electromagnetism to modify experimental methodologies and process data. 6. Investigate phenomena associated with gravity and motion, or electromagnetism through an experiment.	• a considered rationale for the experiment • justified modifications to the methodology • a specific and relevant research question • a methodology that enables the collection of sufficient and relevant data • appropriate use of genre and referencing conventions	5	1.10 1.8
Finding	1. Describe ideas and experimental findings about gravity and motion, or electromagnetism 6. Investigate phenomena associated with gravity and motion, or electromagnetism through an experiment.	• considered management of risks/ethical issues/ environmental issues • collection of sufficient and relevant raw data • fluent and concise use of scientific language and representations	5	1.11
Analysing	2. Apply understanding of gravity and motion, or electromagnetism to modify experimental methodologies and process data. 3. Analyse experimental data about gravity and motion, or electromagnetism	• correct and relevant processing of data • thorough identification of relevant trends/patterns/ relationships • thorough and appropriate identification of the uncertainty and limitations of evidence	5	1.12
Interpreting and evaluating	4. Interpret experimental evidence about gravity and motion, or electromagnetism 5. Evaluate experimental processes and conclusions about gravity and motion, or electromagnetism	• justified conclusion/s linked to the research question • justified discussion of the reliability and validity of the experimental process • suggested improvements and extensions to the experiment that are logically derived from the analysis of evidence	5	1.13
Total			**20**	

The final report for the student experiment may be organised under the criteria headings in the instrument-specific marking guide (ISMG); forming, finding, analysing and interpreting and evaluating. However, this is not mandated, and you may elect to organise your report in a different but logical order using alternate headings.

Note that items such as title or contents pages, the abstract, appendixes, bibliography or reference list and in-text references are not included in the word count. The contents of the appendix are not used for determining levels of achievement.

The headings and sub-headings in Table 1.9.2 show one possible structure of a student experiment report, and alternate positionings of the conclusion section (*).

TABLE 1.9.2 Possible student experiment structure

Forming	Rationale
	Research question
	Modifications
Finding	Risk assessment
	Raw data
Analysing	Sample calculations
	Processed data
	Analysis
Interpreting and evaluating	Conclusion*
	Evaluation of experimental process (reliability and validity)
	Improvements and extensions
	Conclusion*
	Reference list/Bibliography
	Appendix

1.10 Forming

RATIONALE

The student experiment uses a completed class practical or simulation as a basis for further experimentation. This means that the rationale will show an idea flow which begins with an original experimental result and uses scientific reasoning to propose a new and related question (Figure 1.10.1). Often the same or similar experimental apparatus is used but independent and/or dependent variable(s) are altered. Conversely, a new experimental design and equipment is used to investigate the topic.

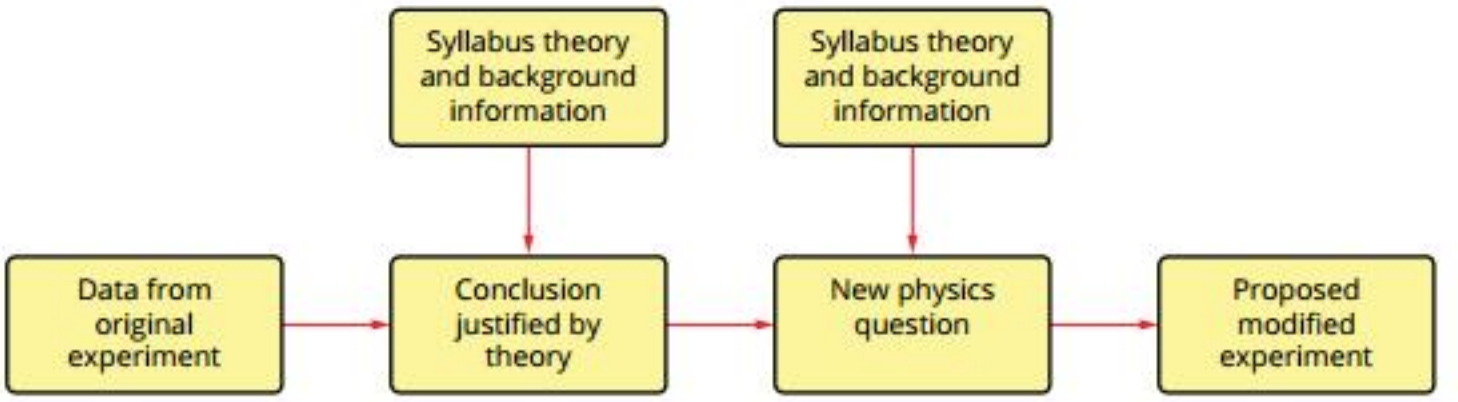

Syllabus theory and background information
Syllabus theory and background information
Data from original experiment
Conclusion justified by theory
New physics question
Proposed modified experiment

FIGURE 1.10.1 Idea flow for reasoning process in rationale. A new physics question is developed from physics understanding and the result of the original experiment.

Background information

The physics concepts of both the original experiment and the proposed new experiment need to be described but it is important to restrict this to the necessary detail; a full topic explanation or literature review is not required. Make sure that key syllabus concepts are included using relevant equations, structures and diagrams. Background concepts need to be referenced by scientific literature using in-text referencing. You will need to read widely but are advised to limit your use of physics concepts that are beyond the scope of the syllabus. If your original experiment and proposed new experiment cannot be explained using syllabus concepts from the appropriate unit, you will need to change your experimental focus. While science understanding of Unit 1 and Unit 2 are formative in the concepts of Units 3 and 4, a summative Student Experiment cannot be based on science understanding of Units 1 and 2. Your explanation of background information demonstrates understanding and knowledge of the direct, and possibly indirect, relationship between the independent and dependent variables and controlled or measured variables.

The syllabus states that the task requires students to:

"research relevant background scientific information to inform the modification of the research question and methodology"

Here we see:

- 'relevant' which means background scientific information relevant to the syllabus as well as relevant to your experiment
- 'inform' which means you have used science concepts to identify a new experiment
- 'modification,' the new experiment is related to the first one but the variable(s) and/or method are modified
- 'research question' refers to a specific research question with proposed dependent and independent variables
- 'methodology,' the details of how you plan to conduct your experiment using scientific method.

Group planning

Parts of the experiment can be completed with your group. For instance, it is appropriate to discuss the findings of the original experiment to be clear about the relationship shown in the data. Also, the group should discuss changes to the method or dependent and independent variables which may be appropriate. However, the rest of the investigation including analysis, evaluation and report writing is an individual task.

Discuss with your peers the ideas already learnt in class about the topic and possible or expected relationships which could be investigated (Figure 1.10.2). This relationship will be the focus of your research question. In addition, you may propose a refinement of equipment or methodology which will need to be discussed and clarified with your teacher. Check that your school laboratory has the resources for you to perform the experiment or investigate the topic. Choose a topic that can provide clear measurable data that shows how variable y depends on variable x.

Consider the following when developing the modified experiment:

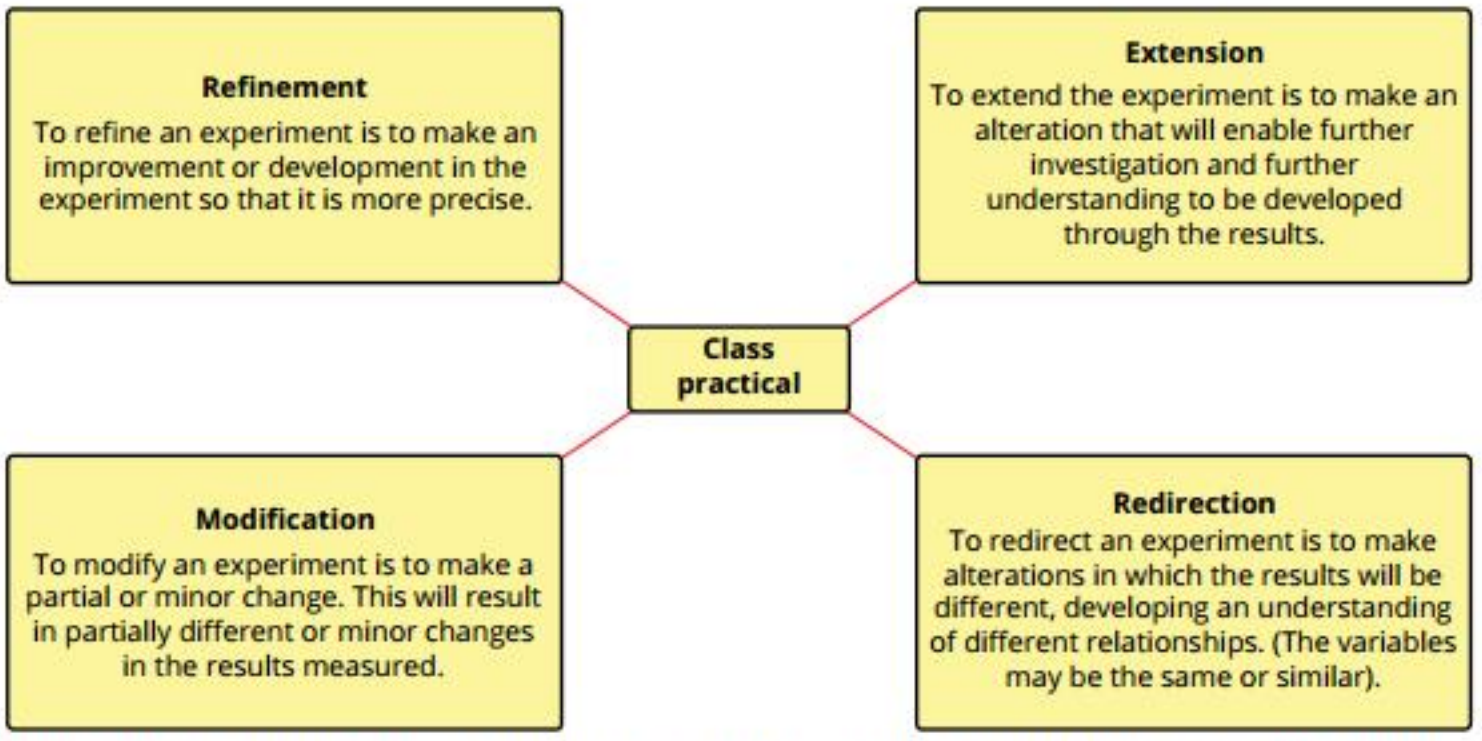

Refinement
To refine an experiment is to make an improvement or development in the experiment so that it is more precise.
Extension
To extend the experiment is to make an alteration that will enable further investigation and further understanding to be developed through the results.
Class practical
Modification
To modify an experiment is to make a partial or minor change. This will result in partially different or minor changes in the results measured.
Redirection
To redirect an experiment is to make alterations in which the results will be different, developing an understanding of different relationships. (The variables may be the same or similar).

FIGURE 1.10.2 Changes that can be made to a class practical to develop the student experiment. See 'Modifications' below for further information.

Table 1.10.1 shows examples of modifying an original experiment into a topic of interest for a student experiment.

TABLE 1.10.1 Examples of modifying a practical into a student experiment

Original experiment	Possible modified experiments
Conduct an experiment to investigate the proportional relationship between heat and temperature change.	Does the proportionality between heat and temperature change vary with mass?
	Is the accuracy of the proportionality constant between heat and temperature change improved by additional trials?
	Can the experimental method be used to determine the proportional relationship between heat and temperature change for other substances?
	Can the apparatus or method be altered to limit heat loss and increase accuracy of the investigation?

Defining the variables and data collection

The factors that can change during your experiment or investigation are called variables. An experiment or investigation determines the relationship between variables by measuring the results. There are four categories of variables (Figure 1.10.3). You should have only one independent variable. Otherwise, you could not be sure which independent variable was responsible for changes in the dependent variable (the results). It is best to think of a single variable (independent variable) that may influence the measured outcome (dependent variable). Use clear dependent and independent variables, and be specific about the number of trials. The more variables that are altered (including **measured variables** and **controlled variables**), the more complex the task becomes.

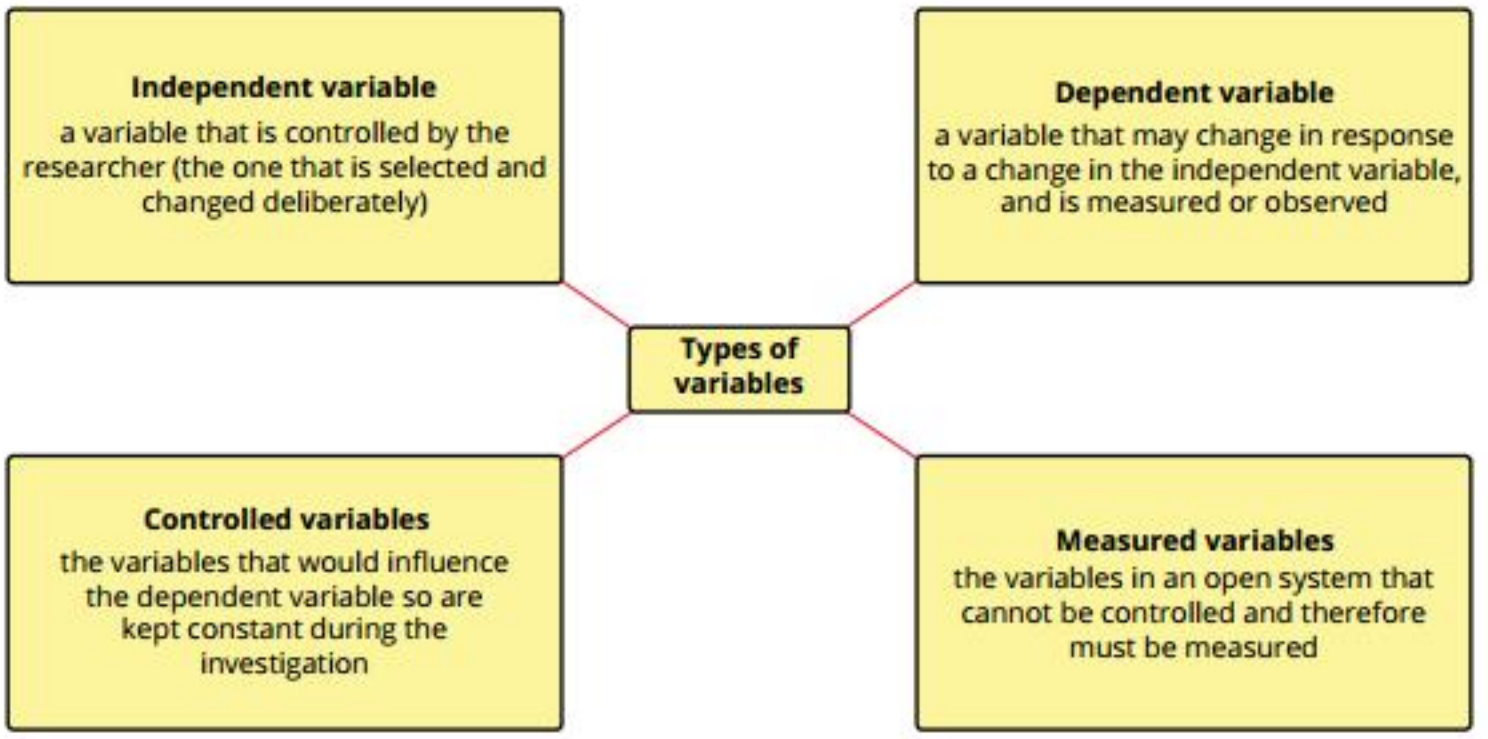

Types of variables
Independent variable
a variable that is controlled by the researcher (the one that is selected and changed deliberately)
Dependent variable
a variable that may change in response to a change in the independent variable, and is measured or observed
Controlled variables
the variables that would influence the dependent variable so are kept constant during the investigation
Measured variables
the variables in an open system that cannot be controlled and therefore must be measured

FIGURE 1.10.3 The four types of variables in experiments

To ensure an investigation is **valid**, it should be designed so that only one variable is being changed by the researcher at a time, and only one variable is changing in response. The remaining variables must remain constant so that meaningful conclusions can be drawn about the relationship between variables. In junior science we learn "Change one thing, measure one thing, keep everything else the same". In your Rationale and Research Question discussions with your group and teacher you will consider the:

- independent variable (the thing that is changed)
- dependent (measured) variable
- controlled variables (parts of the equipment, method and conditions that are constant)
- appropriate raw data that will be collected (quantitative versus qualitative), and how each will be measured, collected or controlled.

Data can either be qualitative or quantitative. **Qualitative data** is descriptive and unmeasurable and uses descriptions or adjectives to record observations. It cannot be statistically analysed. **Quantitative data** is empirically measurable and uses instruments to record observations as numbers with units.

Qualitative and quantitative data have further subsets in each category (Figure 1.10.4).

Qualitative data: can be observed but not measured.

They can only be sorted into groups or categories such as the colour of light or shape of a magnetic field.

Quantitive data: can be measured.

Height, mass, volume, temperature, intensity and time are all examples of quantitative data.

Nominal data

Variables are categorical variables in which the order is not important.

Example 1: the type of metal, type of apparatus

Example 2: the planets in our solar system

Discrete data

Variables consist of only integer numerical values, not fractions.

Example 1: the number of springs connected together

Example 2: the energy levels in atoms

Ordinal data

Variables are categorical variables in which order is important and groups have an obvious ranking or level.

Example 1: the level of brightness of light globes

Example 2: the apparent brightness of stars as seen from Earth

Continuous data

Variables allow for any numerical value within a given range.

Example 1: the measurement of height, temperature, volume, mass and intensity

Example 2: time for cart to slide down a ramp

FIGURE 1.10.4 Quantitative and qualitative variables

Measurement of temperature requires an instrument and provides quantitative data whereas sensing the production of heat by touch provides qualitative data (Figure 1.10.5).

FIGURE 1.10.5 (a) Using a thermometer or a wireless temperature sensor will measure temperature empirically and provides quantitative data that can be analysed statistically. Processing empirical data can produce discrete, explicit and comparative analysis. (b) Feeling heat radiating from a heater is an example of qualitative data as it is based on personal observation. Qualitative data cannot be statistically analysed.

Depending on the experiment, it may be appropriate to record the qualitative observation (e.g. brightness of light), or to measure quantitative results (e.g. voltage).

Sourcing appropriate equipment and materials

You will need to decide on the materials, technology and instrumentation that will be used to carry out your experiment or investigation. It is important to find the right balance between items that are easily accessible and those that will obtain accurate and precise results. The precision of the chosen instrumentation affects the level of measurement uncertainty and is recorded as a ± value in the raw data table. Instrumentation choices are described in 'Justified modifications to the methodology'.

Sample size

Because a single measurement or experimental result could be affected by errors, **replication** of samples within an experiment and **repeat trials** are key components of reliability. A larger sample size will improve:

- the representation of the phenomenon
- the natural variation, errors and uncertainty
- the results by offering more evidence to support the experimental results
- aids with repeatability and therefore reliability.

Consider the practicalities of timing and validity of data in determining the number of trials and the number of independent variables tested. Given that 10 hours are allocated to planning the experiment, performing the experiment and writing the report, 25 trials is generally sufficient. This represents 5 different values of the independent variable, with 5 trials each.

WRITING A RESEARCH QUESTION

When you have decided on a dependent variable, independent variable, controlled variable(s) and method of testing you are ready to write your research question.

A research question directs and describes the scientific inquiry activity. Its purpose is to focus the student experiment, inform the direction of the research, and guide all stages of inquiry, analysis, interpretation and evaluation.

The question determines the experiment and the experiment is testing the question. A research question should:

- be specific and relevant to the class experiment
- clearly identify the subject matter of the experiment
- specify the scope or conditions of the inquiry
- aim to find trends or patterns of relationships between two variables.

A research question should state the independent and the dependent variables. It should ask if the independent variable will affect the dependent variable. The research question must specifically outline variables in a way that are measurable; this also allows the research question to be answered.

An example is shown below.

dependent variable

independent variable

'What is the relationship between the length and the period of a simple pendulum if the angle of release and mass of the bob are constant?

A well-constructed research question should have the following characteristics.

- It should include measurable variables—the independent variable and the dependent variable.
- It should have a guiding word, such as *how*, *what* or *will*.
- It should be phrased so that a definitive answer can be developed.
- It should state key (not all) controlled variables or conditions

Table 1.10.2 gives examples of constructed research questions.

TABLE 1.10.2 Structuring a research question

Guiding word(s)	Example research questions
what	What is the relationship between cross sectional area and resistance in a series circuit, if the resistivity and voltage remain constant?
will	Will increasing the mass of an object affect fall time, if the size of the object and drop height remain constant?
how	How does the amount of radiation detected 10cm from an Americium-241 source change as the amount of shielding between the source and the detector is increased?
can	Can the current within a series circuit be reduced by increasing the resistance of a component?
do/does	Does the quantity of water used in calorimetry effect the accuracy of determining the specific heat capacity of a substance?

Evaluating your research question

Once a research question has been developed, stop to evaluate it before progressing.
Follow the prompts in the chart below (Figure 1.10.6) to refine and improve it.

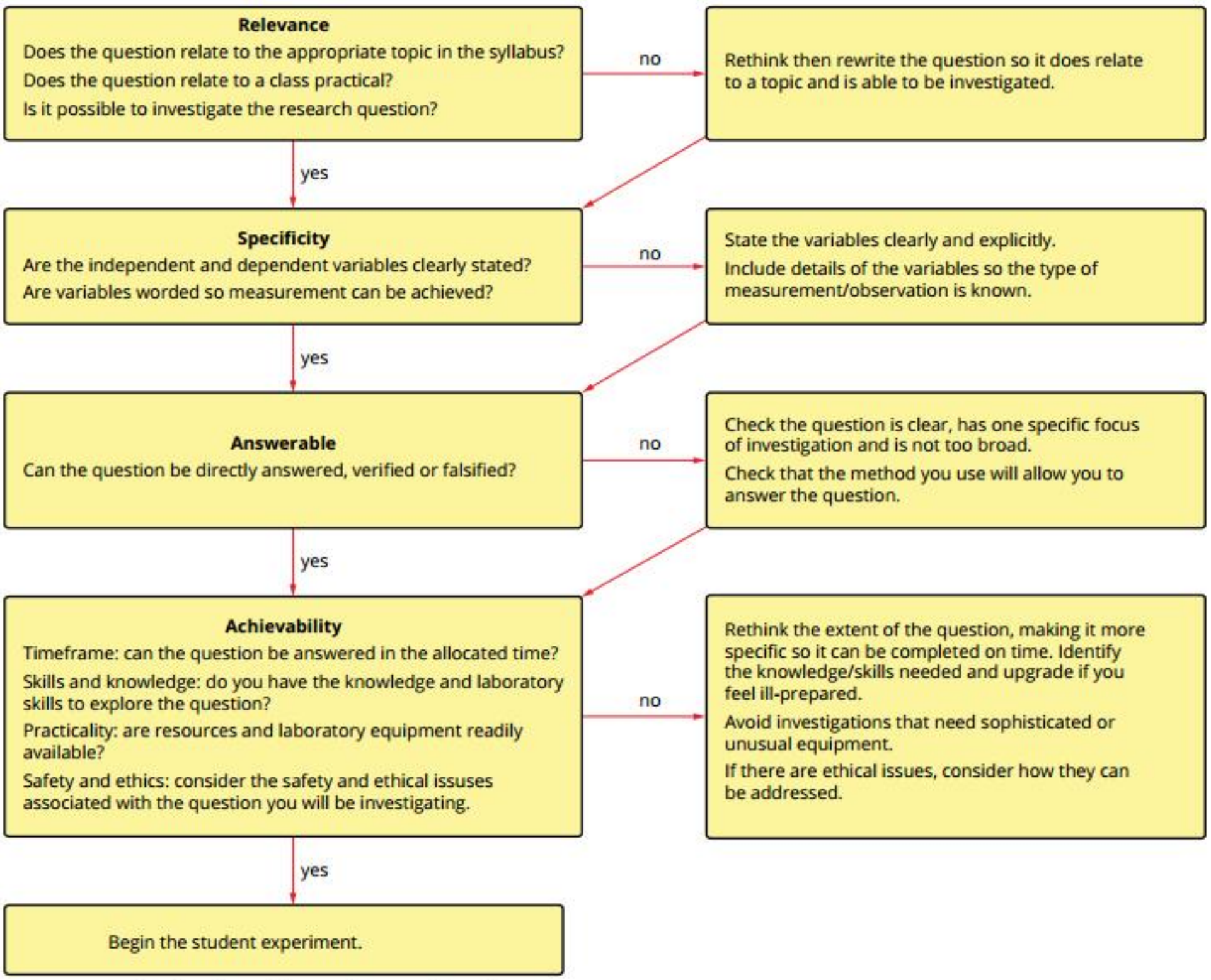

Relevance
Does the question relate to the appropriate topic in the syllabus?
Does the question relate to a class practical?
Is it possible to investigate the research question?
no
Rethink then rewrite the question so it does relate to a topic and is able to be investigated.
yes
Specificity
Are the independent and dependent variables clearly stated?
Are variables worded so measurement can be achieved?
no
State the variables clearly and explicitly.
Include details of the variables so the type of measurement/observation is known.
yes
Answerable
Can the question be directly answered, verified or falsified?
no
Check the question is clear, has one specific focus of investigation and is not too broad.
Check that the method you use will allow you to answer the question.
yes
Achievability
Timeframe: can the question be answered in the allocated time?
Skills and knowledge: do you have the knowledge and laboratory skills to explore the question?
Practicality: are resources and laboratory equipment readily available?
Safety and ethics: consider the safety and ethical issuses associated with the question you will be investigating.
no
Rethink the extent of the question, making it more specific so it can be completed on time. Identify the knowledge/skills needed and upgrade if you feel ill-prepared.
Avoid investigations that need sophisticated or unusual equipment.
If there are ethical issues, consider how they can be addressed.
yes
Begin the student experiment.

FIGURE 1.10.6 Steps to refine and improve the research question

A research question proposes a question about the relationship between the dependent and independent variables if the investigation. It is a required component of the Student Experiment. A hypothesis defines the expected link between dependent and independent variables and supports the research question but is not an assessed component of the ISMG.

Formulating a hypothesis

A hypothesis may be developed. A hypothesis is a statement that proposes a relationship between variables and an expected result of the experiment; it is based on some level of understanding. Having completed extensive background research (rationale), you will have the means and understanding to state the expected results in the form of a hypothesis.

The student experiment does not require a hypothesis and it may not always be appropriate or beneficial. Because the hypothesis proposes a specific relationship between the independent and dependent variables, the hypothesis can either be supported or refuted by the results. Note that a hypothesis can be supported or confirmed, but not 'proved', whereas it can be disproved (refuted).

The following examples (Table 1.10.3) demonstrate the relationship between dependent and independent variables and a research question:

TABLE 1.10.3 Research question examples

Relationship between dependent and independent variables	Research question
As the temperature of the gas increases, the volume of the gas will increase.	How does the volume of air in a syringe change as the temperature of the air is increased from 20 to 80 degrees Celsius?
The rate of reaction will increase and time for production of 25 mL gas will decrease as the temperature of the reaction mixture increases.	Does the time taken for the production of 25 mL of hydrogen gas decrease as the temperature of the solution of 50 mL 0.5 M hydrochloric acid and 5 g zinc is increased?
The accuracy of the measured molar enthalpy of combustion of ethanol will be increased by performing multiple calorimetry experiments.	Does burning different masses of ethanol (2 g 4 g 6 g) in multiple calorimetry experiments improve the accuracy of the determination of the molar heat of combustion?

MODIFICATIONS

The previous section shows how complex the Forming (planning) part of the student experiment is. You (and your group and teacher) will have decided on key aspects of the modified experiment - independent, dependent and controlled variables—identified a procedure and equipment for use, and written a research question. It is necessary to document each modification to the original experiment in your report and justify each proposed modification.

The methodology of your experiment is a specific step-by-step procedure which your teacher will require you to prepare prior to the experiment. However, this detail is generally not required in the report. In the modifications section, write an overview of the original method (use an in-text reference) in paragraph form and provide a written or tabulated description of the modifications proposed. Include specific details about instruments and techniques employed, and number of trials. Each modification is justified by stating the type of change ('refine', redirect' or 'extend') and how it will improve the investigation. If possible, link each modification to random and systematic error. An example is shown in Table 1.10.4.

TABLE 1.10.4 Example modifications to original experiment with justification

	Modification	Justification
Refinement	Replacing a foam projectile with a ball bearing	Reduces the impact of drag on projectile motion, reducing systematic error from drag and random error from wind.
Refinement	Collection of more data – five trials for each value of the independent variable rather than one.	Improves accuracy by providing an average and uncertainty.
Redirection	Measuring how the strength of a magnetic field varies with angle.	Changes the independent variable to investigate another aspect of the theoretical relationship.
Extension	Measure the horizontal displacement of projectile motion between 0-degrees and 180-degrees.	Measures the behaviour across all values to see if the relationship holds across the entire range.
Refinement	Replace stop watches with video analysis.	Provides more reliable readings of time and reduces random error.

One way to modify an original experiment is to improve the precision of the laboratory equipment. With higher-precision instruments, there is less chance of error and lower uncertainty in the measurement. Table 1.10.5 demonstrates the benefits of greater-precision instruments through lower measurement uncertainty.

TABLE 1.10.5 The difference in precision between instruments: (a) a glass thermometer with a precision of ±2.5°C; (b) a measuring beaker with a precision of ±5 mL; (c) a metal ruler with a precision of 1 mm (d) a digital laser thermometer with a precision of ±0.2°C; (e) a measuring cylinder with a precision of ±0.25 mL, and (f) a micrometer with a precision of 0.005 mm

Lower precision instruments		
a	b	c
Higher precision instruments		
d	e	f

PUTTING IT ALL TOGETHER

The following sample experiment report below is an example of a modification of the investigation of linear motion from Unit 2. This modification is no longer suitable for Unit 2 (the chosen modification is no longer linear motion, taking it outside of scope of Unit 2). This was intentionally selected to reduce the impact on student responses.

It follows the ISMG criteria and may be used as a reference tool.

An investigation into the relationship between pendulum length and period for a simple pendulum as a method of verifying the acceleration due to gravity

Rationale

Gravity is a form of acceleration and is generalised across the surface of the Earth as 9.81 $m s^{-2}$. (WDC for Geophysics, Beijing, 2015). This value would hold true everywhere if the Earth existed as a perfect sphere. Earth is actually an "oblate spheroid" which is bulging at the equator and flatter at the poles (WDC for Geophysics, Beijing, 2015). Furthermore, gravitational force is also somewhat dependent on mass (second law of motion) and so "the strength of gravity's pull on an object may be stronger or weaker at different locations, depending on Earth's inner structure and topography". For example, places with more mass present (e.g a mountain) will have stronger gravitational forces than places with less mass (e.g a valley) (Patel, 2023). The goal of this experiment will be to verify the expected/predicted value of gravity, 9.81 $m s^{-2}$.

The original experiment conducted in class was a freefall experiment where a ball was dropped from various heights (displacements) and the fall time was recorded. The experimental uncertainty was quite large ($9.38 \pm 0.51\ m s^{-2}$) only barely containing the expected value for gravity. Analysis revealed that these large uncertainties were due to the random error of human reaction time, as well as drag decelerating the falling ball. This can be seen in the drag equation below where drag (D) increases with velocity (v) (Benson, 2015):

$$D = C_d \times r \times \frac{1}{2} v^2 \times A$$

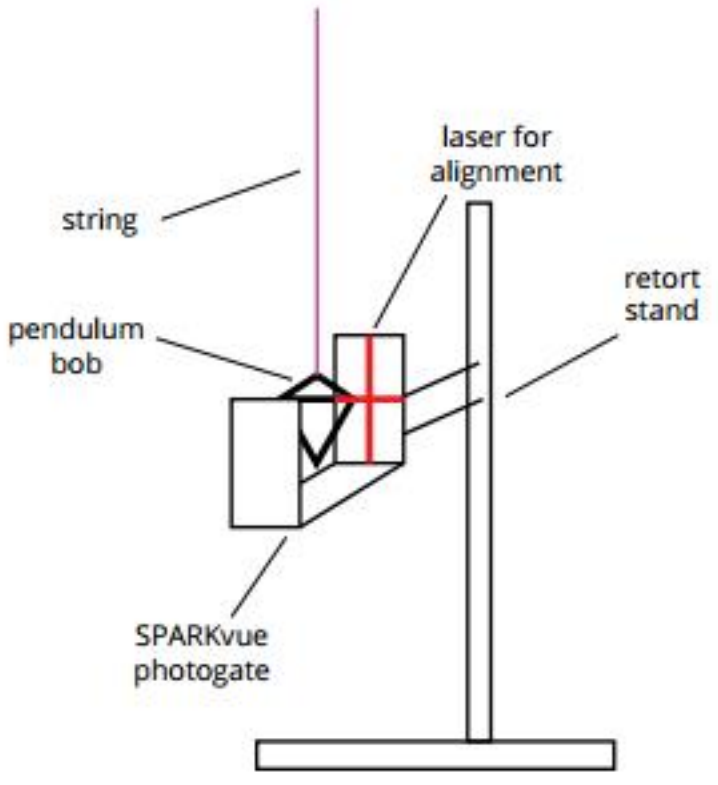


FIGURE 1 Experimental setup

To overcome these limitations, it was decided to modify the experiment to reduce velocity to minimise the effect of drag, and to remove the random error introduced by reaction time. This was achieved by redirecting the experiment to investigate a simple pendulum (Figure 1) where a bob (142.45 g mass and 23.24 mm diameter) is suspended from a string and released at an angle of less than 15° (The Physics Classroom, 2023). A pendulum was chosen as this will limit velocity while still providing a significant duration of motion under gravity. By measuring this duration with photogates, reaction time was removed as a source of error.

The equation for a simple pendulum is:

$$T = 2\pi \sqrt{\frac{l}{g}}$$

where T is the period (s) and l is the length of the string (m). Linearised this gives:

$$T^2 = \frac{1}{g} \times 4\pi^2 l$$

As such, the expected relationship between period and length is $T^2 \propto l$. The constant of proportionality is equivalent to $\frac{1}{g} \times 4\pi^2$, allowing for verification of the value of gravity.

Research question

What is the relationship between pendulum length and period for a simple pendulum if the mass of the bob is kept constant and the angle of release is less than 15 degrees?

Modifications to the methodology

The proposed modifications to the methodology are described in Table 1.

TABLE 1 Modifications to the methodology

Modification	Justification
Redirection: Investigating the relationship between pendulum length and period	This limits velocity, which limits drag. This reduces the impact of a confounding variable allowing for increased accuracy. Pendulum length and period were chosen as these are most similar to fall time and height from the original experiment.
Refinement: Stopwatches were replaced with photogates	This removes reaction time from the experiment, improving precision.

1.11 Finding

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- conduct a risk assessment
- undertake an experiment encompassing sufficient and relevant data
- collect and present data.

RISK ASSESSMENT

When planning for an experiment in either the laboratory or outside in the field, it is important for your safety and the safety of others that you consider potential risks. Your report should outline potential risks, how they will be mitigated, and how they will be managed. While the key consideration is for the personal safety of the people in the laboratory, you may need to consider and include a statement about potential ethical considerations or effects on the environment if relevant to your experiment.

Your risk assessment will have three sections:

- hazard—the name of the item or activity that could cause risk
- risk—the possible negative outcome that could occur
- control measures—the practices or processes to avoid the risk.

Often, the original experiment will have used similar equipment and so information from its risk assessment can be used. Check with your teacher regarding new equipment that you are planning to use.

To identify risks, think about the following:

- laboratory rules of the school, for example, procedures for behaviour in a laboratory and procedures for equipment use
- the activity that you will be carrying out including physical issues such as lifting heavy objects or use of projectiles and how you will use any equipment (such as glassware) or chemicals that you will be handling, including sources of heat and electricity.
- the facilities of the laboratory. These include emergency equipment on site, ventilation of the laboratory, facilities such as a fume hood.
- the chemical codes and SDS data (Safety Data Sheet) for chemicals in use. Consider also concentrations of chemicals and hazards associated with products of chemical reactions.
- what protective clothing you should wear, e.g. lab coat and goggles.

Chemical codes

The chemicals at school or in a hardware shop have a warning symbol on the label. These symbols are a chemical code indicating the nature of the contents (Table 1.11.1). In 2017, the Globally Harmonised System of Classification and Labelling of Chemicals (GHS) was introduced in Australia for use in workplaces, including school laboratories.

TABLE 1.11.1 GHS pictograms used as warning symbols on chemical labels

GHS symbol	Use	GHS symbol	Use	GHS symbol	Use
	flammable liquids, solids and gases; including self- heating and self- igniting substances		oxidising liquids, solids and gases, may cause or intensify fire		explosion, blast or projection hazard
	corrosive chemicals; may cause severe skin and eye damage and may becorrosive to metals		gases under pressure		fatal or toxic if swallowed, inhaledor in contact with skin
	low level toxicity; this includes respiratory, skin and eye irritation, skin sensitisers and chemicals harmful if swallowed, inhaled or in contact with skin		hazardous to aquatic life and theenvironment		chronic health hazards;this includes aspiratory and respiratory hazards, carcinogenicity, mutagenicity and reproductive toxicity

Safety Data Sheets

Each chemical substance has an accompanying document called a **Safety Data Sheet (SDS)** (Figure 1.11.1). A SDS contains important safety and first aid information about each chemical you commonly use in the laboratory. The SDS provides employers, workers and health and safety representatives with the necessary information to safely manage the risk of hazardous substance exposure.

1. IDENTIFICATION OF THE MATERIAL AND SUPPLIER

Product identifier

Product Name HYDROCHLORIC ACID - 20% OR GREATER

Supplier
Edwards & Tubbs Operations Pty Ltd
ABN: 51 444 444 444
13 Royston Vasey Street
Melbourne 3000
Australia

Emergency telephone number **1900 654 321 (ALL HOURS)**

2. HAZARDS IDENTIFICATION

GHS Classification

Classified as dangerous goods in accordance with the Australian Code for the Transport of Dangerous Goods by Road and Rail (ADG).

Classified as a hazardous chemical in accordance with the criteria of Safe Work Australia - Globally Harmonized System (GHS).

Corrosive to metals	Category 1
Skin corrosion/irritation	Category 1 Sub-category B
Serious eye damage/eye irritation	Category 1
Specific target organ toxicity (single exposure)	Category 3

SIGNAL WORD: Danger

Hazard statements
H290 - May be corrosive to metals
H314 - Causes severe skin burns and eye damage
H335 - May cause respiratory irritation

Precautionary Statements - Prevention
Keep only in original container
Do not breathe fume, gas, mist, vapours, spray
Wash face, hands and any exposed skin thoroughly after handling
Use only outdoors or in a well-ventilated area
Wear protective gloves / protective clothing / eye protection / face protection

FIGURE 1.11.1 Extracts of a Safety Data Sheet (SDS) for concentrated hydrochloric acid. The SDS alerts the reader to any potential hazards when using a substance, including appropriate measures to reduce risk of harm.

All schools store SDS and chemical code information for materials in use in laboratories and these must be consulted when planning investigations. Online platforms such as RiskAssess allow quick access to these data bases for a planned experiment. In these types of software programs, the potential hazards for each aspect of the experiment are provided when proposed equipment and materials are listed. Handling procedures are also suggested.

It is important to note that to address the syllabus requirement to show 'considered management of risk', you need to do more than downloading a data sheet, or using risk assessment software. The syllabus specification requires you to 'conduct a risk assessment and account for risks in the methodology.' This means that, as described above, the three factors of (i) risk (ii) possible negative outcome and (iii) prevention need to be aligned and clearly presented in the report. This can be done by writing a paragraph or preparing a table (Table 1.11.2). The supporting data sheets or risk assessment files should be placed in the Appendix and key facts used in your report.

TABLE 1.11.2 Sample risk assessment table showing hazards, risks and control measures to reduce the risks

Hazard	Risk	Control Measures
Neodymium magnets	May shatter if released form a distance. May pinch skin if handled improperly.	Magnets were affixed in place by teacher and taped down so they could not be moved. Safety glasses worn.
Power pack	Becomes hot with use. Hazardous around liquid.	Power pack turned on briefly for data recording then turned off again immediately to prevent temperature build up. No liquids used near experiment. Group members instructed on location and use of emergency power switch.
Resistor	Can become very hot and burn out if power is left on.	Power pack turned on briefly for data recording then turned off again immediately to prevent temperature build up. If resistor becomes burned out, allow to cool before attempting to replace. Group members instructed on first aid kit location and burn treatment protocol.

Risk controls

The hierarchy of risk controls is shown in Figure 1.11.2. It is organised from the most effective to least effective. The most used risk control measure that addresses the majority of risks is personal protective equipment. The least common but most protective control measure is eliminating the risk from the scientific investigation.

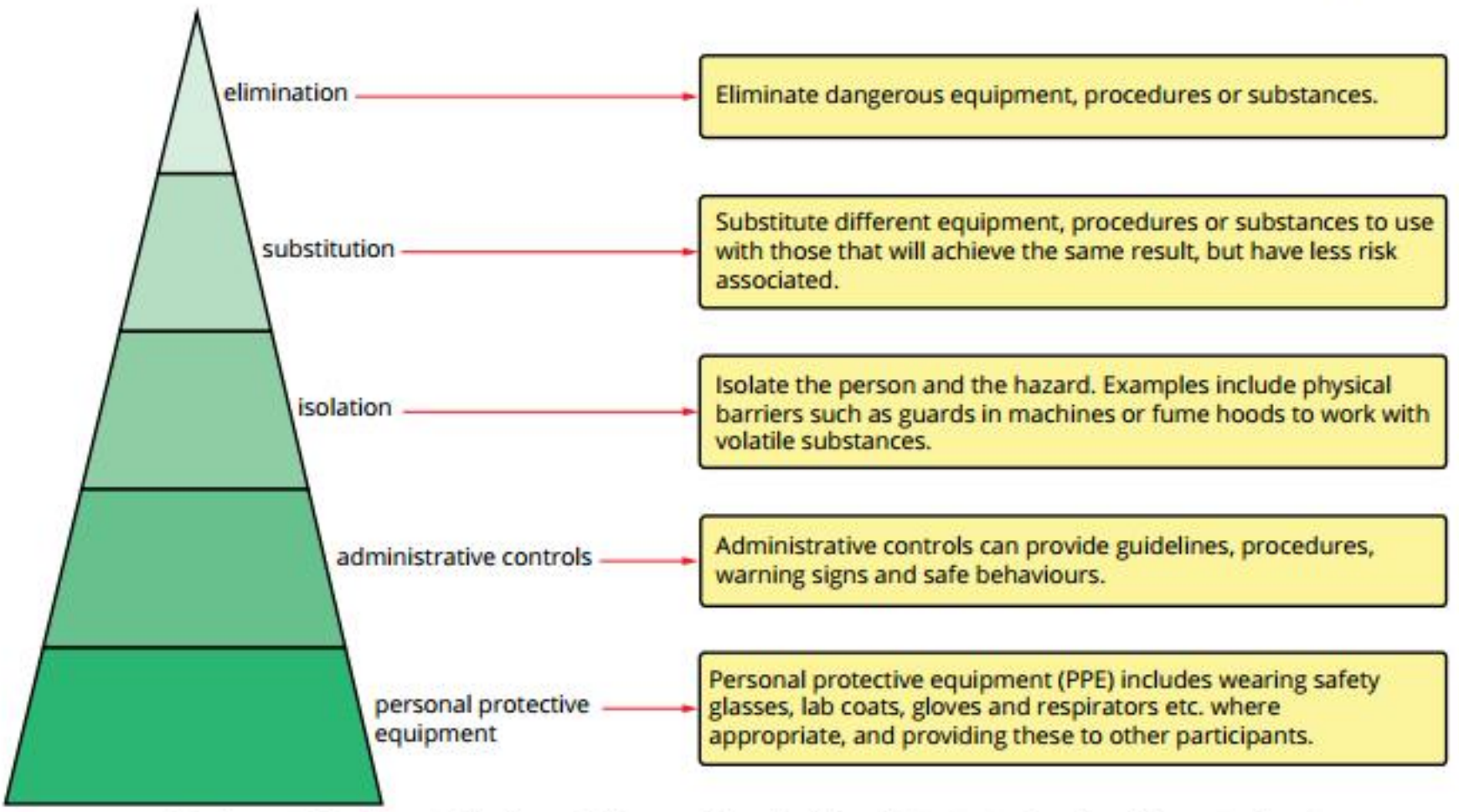

elimination
Eliminate dangerous equipment, procedures or substances.
substitution
Substitute different equipment, procedures or substances to use with those that will achieve the same result, but have less risk associated.
isolation
Isolate the person and the hazard. Examples include physical barriers such as guards in machines or fume hoods to work with volatile substances.
administrative controls
Administrative controls can provide guidelines, procedures, warning signs and safe behaviours.
personal protective equipment
Personal protective equipment (PPE) includes wearing safety glasses, lab coats, gloves and respirators etc. where appropriate, and providing these to other participants.

FIGURE 1.11.2 The hierarchy for risk control is shown in this pyramid, marked from bottom to top in order of increasing importance.

Personal protective equipment

Everyone who works in a laboratory wears items that help keep them safe, such as those shown in Figure 1.11.3. These items are called **personal protective equipment (PPE)** and include:

- safety glasses
- shoes with covered tops
- disposable gloves when handling certain chemicals
- a disposable apron or a lab coat if there is risk of damage to clothing.
- a hair net or tied back hair for using a Bunsen burner.

FIGURE 1.11.3 Examples of PPE shown are protective eye wear, lab coats and gloves.

Environmental and ethical considerations

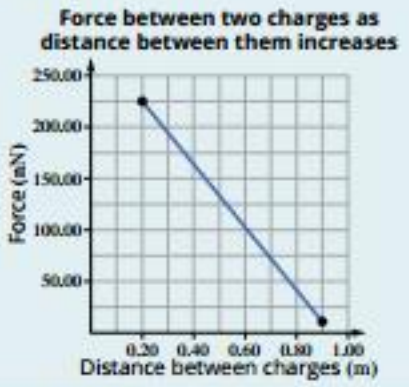
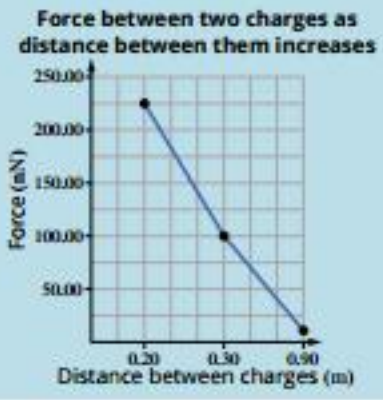
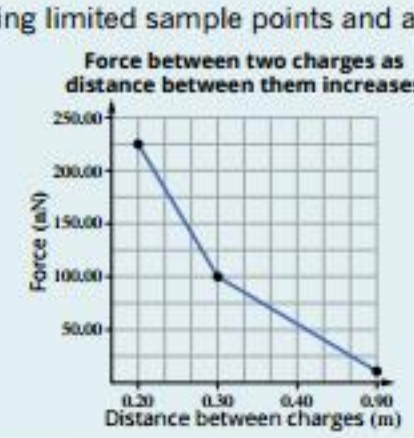
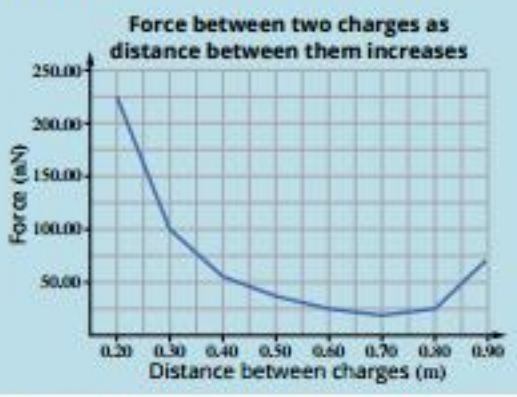
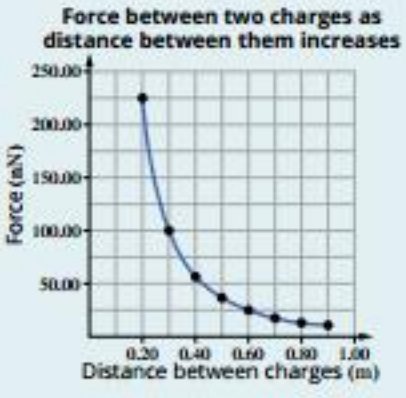
When planning an investigation, identify any relevant environmental and ethical considerations and evaluate the mitigation of these issues. For example, the metals and acids used in some batteries can have environmental impacts if disposed of improperly.

Ethics is a set of moral principles by which your actions can be judged as right or wrong. Scientists must obtain approval from an ethics committee and follow ethical guidelines relating to animals and humans. School physics investigations generally only have minor ethical issues, if any. However, consider if during the experiment, one party or group benefits over another, or are there real-world connotations of the investigation not accepting of the rights of a community group.

COLLECTION OF SUFFICIENT AND RELEVANT RAW DATA

Enough data needs to be collected to substantiate whether a relationship exists between the dependent and independent variables. For the data to be *relevant*, the investigation must collect values for independent and dependent variables as described in the Research Question. For the data to be *sufficient* means to have appropriate sample size in terms of an appropriate number of replicate trials and an appropriate number of variations of the independent variable. Sample size will impact on the accuracy of the data, the uncertainty within the data collected, and the ability to interpret the data. In general, a minimum of five data points and five measurements per data point (five trials) are needed. This provides a sample size consistent with sufficient and relevant data and allows for the removal of some outliers without substantially impacting the overall quality of the data. Table 1.11.3 outlines examples of sample size and their effect on the results of an experiment.

TABLE 1.11.3 Examples of sample size and their effect on the results of an experiment

Examples of analysed data	Effect of sample size on analysis
A line graph with two sample points 	With only two individual sample points, this graph suggests an inappropriate linear relationship for the force acting between two charges as the distance between them increases.
Line graph with three sample points and an uneven scale 	The scale on the horizontal axis is not evenly spread, which distorts the shape of the graph. These results suggest an incorrect relationship for the force acting between two charges as the distance between them increases.
Line graph showing limited sample points and an uneven scale 	The chosen number of individual sample points is insufficient, because the true relationship is not fully displayed. The next example of displayed results provides more validity for the relationship.
Line graph based on data that had no replicates 	These results are due to only a single measurement for each individual sample point. In this example, the measurements for distances greater than 0.70 m are incorrect. These results suggest an incorrect relationship between the variables.
Scatter graph with appropriate number and distribution of sample points 	The number of individual sample points here best demonstrates the relationship between the variables. Note that a scatter plot has been used rather than a line graph.

Having determined your sample size, check with your teacher that your protocol and schedule (methodology) are appropriate. You need to be able to perform your experiment independently, in the time available in the school laboratory, and with minimal support from your teachers and school laboratory staff.

It is common for experimentation and testing not to go according to plan even if comprehensive background research has been undertaken. Refinements such as reducing or increasing the sample size may be necessary due to timing issues, change to instrumentation or resource limitation.

If the expected data is not obtained, do not worry. Sometimes a different point of view, such as from a fellow student or a teacher, is all that is needed to find a solution. If the data can be critically and objectively evaluated (limitations of the investigation are identified) in your report, the work is worthwhile. Unexpected data provides students with an opportunity to add depth to their experimental report by critically evaluating issues in the experiment. There may be evidence of extraneous variables (not previously recognised) or confounding factors. Evaluation of the methodology based on evidence collected and suggested improvement(s) is a key section of the scientific report.

Record everything. The initial data set in your journal may contain both quantitative (values and measurements) and qualitative (observations) data. Note any difficulties encountered or trials which were conducted slightly differently; perhaps the experiment was conducted over two lessons resulting in a change in room temperature, a new measuring instrument, or a different person determining the readings. This information may be influential in your analysis and evaluation. With justification, a data point can be identified as an **anomaly** and removed from the data set due to being an outlier. This may be due to a mistake or failure to correctly follow the method (see Data Processing). Nevertheless, all values need to be recorded in the raw data table. Choosing not to record certain measurements or observations is invalid, shows bias and is scientifically fraudulent. Quality scientific analysis processes the raw data as it is and is open to any result.

A workable plan for data collection is for one group member to be responsible for recording. This minimises clutter at the experimental work bench and provides a consistent single data set to share with the group. The recording person should add the measurement uncertainty of each piece of equipment or instrument as a range of data next to the measured value (e.g. measurement ± Δ measurement). Conducting the experiment and collecting data is a group activity, however all subsequent parts of the task (data processing, analysis, evaluating and concluding) are completed individually. Therefore, it is important that the data set is disseminated to the group immediately the experiment finishes.

Electronic data acquisition in schools

Electronic data acquisition takes advantage of highly accurate sensors to collect data directly for processing by a computing device (Figure 1.11.4). There are many sensors, probes and instruments available that can measure a vast variety of phenomena in a single device.

FIGURE 1.11.4 Data acquisition software produces real-time graphs that can be downloaded or printed.

Many smartwatches and apps in phones include digital sensors and **data loggers** (Figure 1.11.5) that can be accessed and used for some class practicals and experiments. The video camera of a phone or tablet is also an excellent means of capturing data, particularly for investigations in kinematics and dynamics.

FIGURE 1.11.5 Many smartwatches and phones have digital sensors and in-built data loggers.

Often one of the measurements is time; the user decides what the other measurement (or variable) is by selecting the type of sensor, or probe, to use. Probes can measure temperature, pH, gas pressure, conductivity, concentration of gases in air, or the amounts of pollutants in the environment along with many more phenomena.

Recording is done accurately and can be continuous or manual, and the measurements are saved electronically. The saved measurements can then be accessed via a computer or directly from the tablet screen. The rate at which measurements are recorded is called the sample rate. Data capture rate can be varied from 100000 times per second through to once an hour, and the duration of recording adjusted to a suitable interval (Figure 1.11.6).

FIGURE 1.11.6 (a) Sensors connected to computing devices such as phones and tablets are readily used in the field. This one is being used to measure the periodic nature in the movement of a playground swing. (b) Many different probes and sensors can attach to a single device, such as in the use of accelerometers and angle sensors to measure the lift of a bar. (c) They can be very precise and measure multiple times per second, such as the frequency and amplitude of air vibrations in sound to record motion. (d) They are usually easy to use and produce results immediately; for example, this sensor measures the temperature of skin on contact.

PUTTING IT ALL TOGETHER

This is the risk management and raw data for the investigation in 1.10 Forming (an investigation into the relationship between pendulum length and period for a simple pendulum as a method of verifying the acceleration due to gravity).

Risk management

TABLE 2 Risk management

Risk	Consequence	Mitigation
Someone could be hit by the bob.	Someone could suffer an injury.	The pendulum will be controlled, and the immediate surrounding area will be cleared before each trial.
Someone could be hit by the ruler.	Someone could suffer an injury.	The ruler will be used with caution and with control.

Results

TABLE 3 Raw data

Length (m, ± 0.001)	Predicted Period, T (s)	Period T (s, ± 0.05)							
		T1	T2	T3	T4	T5	Average	Absolute Uncertainty	Percentage Uncertainty
0.365	1.2123	1.23	1.21	1.21	1.19	1.21	1.21	0.020	1.65%
0.430	1.3158	1.31	1.31	1.32	1.31	1.35	1.32	0.020	1.52%
0.485	1.3974	1.41	1.43	1.41	1.41	1.39	1.41	0.020	1.42%
0.550	1.4881	1.46	1.49	1.48	1.51	1.51	1.49	0.025	1.68%
0.615	1.5736	1.60	1.58	1.57	1.57	1.58	1.58	0.015	0.95%

No significant outliers (> ±10%) were identified.

1.12 Analysing

PROCESSING THE DATA (SAMPLE CALCULATIONS)

Processing the data in numerous ways (including mathematical techniques and graphing) allows elucidation of relationships between variables. You will analyse trends or patterns in the data, uncertainties and limitations, outliers and results of significance. To prepare your **processed data**, you should consider which of the following mathematical techniques are suitable in your investigation:

- Average (mean)
- Measurement uncertainty (absolute measurement uncertainty and percentage measurement uncertainty)
- Propagation of measurement uncertainty (addition, subtraction, multiplication, division)
- Primary graph (scatterplot showing raw data)
- Secondary graph (scatterplot showing processed, linearised data with error bars, lines of best, maximum, and minimum fit, and R^2)
- Gradient and intercept analysis
- Uncertainty of the mean and intercept (absolute and percentage)

$$\Delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$$

$$\text{percentage uncertainty (\%)} = \frac{\text{absolute uncertainty}}{\text{measurement}} \times 100$$

- Percentage error

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{measurement}}\right| \times 100$$

These techniques are explained in Part A Working Scientifically and in the Science Inquiry section of the syllabus.

When you have decided which of these techniques are valid for your investigation, prepare a processed data table and include a sample calculation table which shows a single calculation for each. Remember, there are two types of uncertainty – one associated with the measuring equipment (measurement uncertainty) and one associated with the range of trials (uncertainty of the mean). Both of these values can be expressed as the calculated value (absolute uncertainty) or converted to a percent of the measurement or mean that they describe (percentage uncertainty).

Table 1.12.1 shows an example of a processed (linearised) data table (Table 1.12.2) with the primary data for comparison. This data is taken from the investigation from module 1.10.

Results

TABLE 1.12.1 Raw data

Length (m ± 0.001)	Predicted Period, T (s)	Period T (s, ± 0.05)								
		T1	T2	T3	T4	T5	Average	Absolute Uncertainty	Percentage Uncertainty	Maximum Uncertainty
0.365	1.2123	1.23	1.21	1.21	1.19	1.21	1.21	0.020	1.65%	0.05
0.430	1.3158	1.31	1.31	1.32	1.31	1.35	1.32	0.020	1.52%	0.05
0.485	1.3974	1.41	1.43	1.41	1.41	1.39	1.41	0.020	1.42%	0.05
0.550	1.4881	1.46	1.49	1.48	1.51	1.51	1.49	0.025	1.68%	0.05
0.615	1.5736	1.60	1.58	1.57	1.57	1.58	1.58	0.015	0.95%	0.05

No significant outliers (> ±10%) were identified.

TABLE 1.12.2 Linearised data

Length $(m \pm 0.001)$	Predicted Period T (s)	Period-squared T^2 (s^2)								
		T1	T2	T3	T4	T5	Average	Absolute Uncertainty	Percentage Uncertainty	Propagated Uncertainty
0.365	1.2123	1.51	1.46	1.46	1.42	1.46	1.46	0.048	3.31%	0.06
0.430	1.3158	1.72	1.72	1.74	1.72	1.82	1.74	0.053	3.05%	0.05
0.485	1.3974	1.99	2.04	1.99	1.99	1.93	1.99	0.056	2.84%	0.06
0.550	1.4881	2.13	2.22	2.19	2.28	2.28	2.22	0.074	3.34%	0.07
0.615	1.5736	2.56	2.50	2.46	2.46	2.50	2.50	0.048	1.90%	0.05

When calculations are performed with data values, the uncertainties associated with these values are combined in a process called propagating uncertainties. For example, if a density value is calculated using measured mass and volume, using the relationship density = $\frac{\text{mass}}{\text{volume}}$, then the percentage uncertainty for the measurement of mass (weighing balance) is added to the percentage uncertainty for the measurement of volume (measuring cylinder). This total gives the percentage uncertainty for the density (refer to Part A).

Identification of trends, patterns and relationships

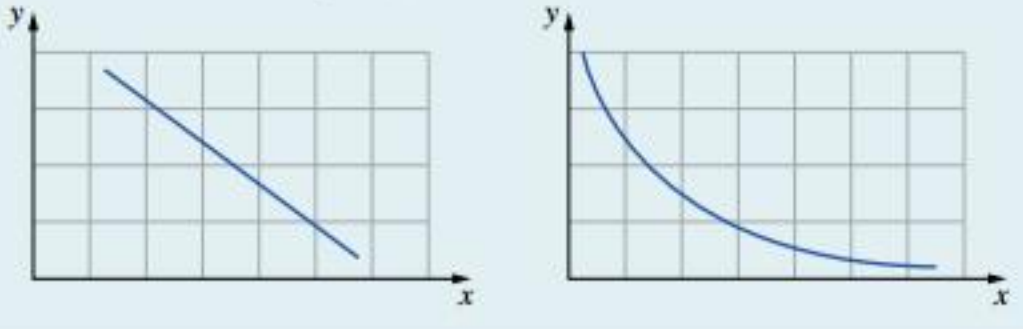
There are several ways to present processed data, depending on its nature, including tables, graphs, flow charts and diagrams. In Physics, this is almost always a scatter plot – a clear visual representation showing a direct or inverse relationship between the dependent variable and the independent variable and if the relationship is linear or not. The Excel program will provide information about the trendline gradient and an R^2 value. By plotting expected values (if known) on the same graph the accuracy of the data is visualised. Several trends which may be identified on your primary graph are shown in Table 1.12.3. Regardless of the type of trend shown on the primary graph, a linearised secondary graph showing lines of best, minimum, and maximum fit should be generated using processed data. See Part A for further information on the linearisation process.

TABLE 1.12.3 Graphs showing different trends and relationships between variables

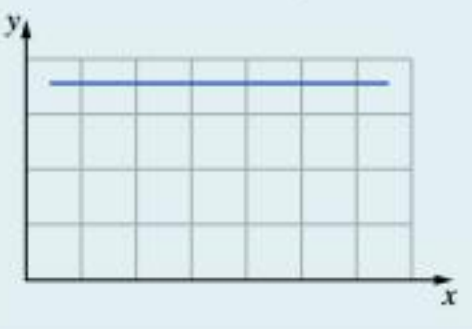
Variables that change in linear or direct proportion to each other produce a straight, sloping trend line.

Variables that change exponentially in proportion to each other produce a curved trend line.

When there is a negative relationship, one variable increases as the other variable decreases. It may be (a) direct or (b) non-linear.



When there is no relationship between two variables, one variable will not change even if the other changes.



Plotting error bars and maximum and minimum trendlines on a graph indicates if the averages shown are significantly different. Overlapping error bars indicate that the difference between these two values is not statistically significant. The graph(s) that you have prepared provide evidence of the relationship between the dependent and independent variables; however, you should describe the features of the graph using a succinct statement:

"As (independent variable) increases (dependent variable) increases/decreases."

It would be useful to follow this with some values from the graph to justify the occurrence of the trend. Further useful analysis could describe the gradient, intercept, R^2 value, similarity/difference to the expected values and whether the error bars overlap or not. Remember, the report has an evaluation section so at this stage it is not necessary to fully explain every aspect of the data. A 'thorough and appropriate identification of trend/patterns/relationships' is what is required here in the Analysis section.

In Physics, it would be appropriate to state the equation from the linearised secondary graph, including uncertainties, in this section. If the chosen experiment is one where the gradient of the secondary graph is meaningful, and contains a relevant proportionality constant, this would be an appropriate place within the report to determine this value. An example of these aspects is shown below.

The experimental linear relationship, including uncertainties was found to be:

$$T^2 = 4.10(\pm 0.74) \times I - 0.02(\pm 0.36)$$

This is consistent with the theoretical relationship of $T^2 \propto I$. The gradient is equal to $\frac{1}{g} \times 4\pi^2$ allowing for an experimental value of g to be determined:

$$4.10 = \frac{1}{g} \times 4\pi^2$$
$$g = 9.63 \text{ms}^{-2} \pm 18.05\%$$
$$g = 9.63 \text{ms}^{-2} \pm 1.74$$

The percentage error was determined by comparing the observed and expected values:

$$\text{percentage error} = \left| \frac{\text{measured} - \text{expected}}{\text{expected}} \right| \times 100\%$$
$$\text{percentage error} = \left| \frac{9.63 - 9.81}{9.81} \right| \times 100$$
$$= 1.83\%$$

Uncertainty, precision and reliability

In Physics, there is always variation in measurements (the terms precision and uncertainty were explained Part A). The level of uncertainty is indicated by:

1 using the measurement uncertainty of the instrument(s) or
2 using the range of trials and dividing by 2 (uncertainty of the mean).

Both can be expressed as a percentage of the value they describe, and both give us an indication of the level of random error in the experiment. When identifying and discussing the level of random error, it is most useful to calculate both and relate the analysis to the higher value. Whichever is the larger source of uncertainty is used to generate the error bars on the secondary graph.

Consider these two uncertainty types in an example dataset (Table 1.12.4) which shows the horizontal displacement of a projectile undergoing horizontally projected motion from a given height on. Firstly, the uncertainty due to the precision in the measurement instrument (measurement uncertainty) is half a division of the scale (±0.005), multiplied by two due to using both ends of the instrument (±0.01 m). When expressed as a percentage of the mean, this is 0.049%.

Secondly, the uncertainty of the mean is calculated using:

$$\text{Uncertainty of mean} = \frac{\text{range}}{2}$$

giving a uncertainty of ±0.40 m. When expressed as a percentage of the mean, this is 1.95%. We see that the uncertainty of the mean is greater than the measurement uncertainty and so we can deduce that the precision of the measurement instrument is only slightly contributing to the level of random error in the experiment. There are further factors contributing to the 1.95% uncertainty.

In addition, as the 1.95% relative uncertainty of the mean is quite low, we can state that the data is precise and reliable and that the level of random error in the experiment is low.

TABLE 1.12.4 Horizontal displacement of a projectile undergoing horizontally projected motion from a given height

Trial	Horizontal displacement of projectile (cm)
1	20.62 ± 0.01
2	20.93 ± 0.01
3	20.13 ± 0.01
4	20.47 ± 0.01
Mean	20.50 ± 0.40

Percentage error, accuracy and limitations of the evidence

The rationale has provided background information that informs the relationship proposed in the research question. This provides your expected trend and, in your analysis, you will state if this trend was obtained. In addition, you may be able to research expected values for the data set that you have collected, or the gradient/proportionality constant you have obtained. If this is the case, it is expected that you will calculate percentage error values for the data points or gradient/proportionality constant.

Percentage error measures how different your data is to expected values and so will allow you to make a judgement about accuracy and validity. Low percentage error indicates low systematic error in the investigation. By researching expected values you are accessing experimental data from scientific laboratories, or the defined values of proportionality constants, and so we expect that the equipment and methodology in a secondary school laboratory is unlikely to accurately replicate these values. Percentage error is likely to be quite high given these limitations. Nevertheless, if a percentage error value is unreasonably high, such as 50%, you can identify a lack of accuracy and the investigation is lacking validity; state this as a limitation.

Again, when identifying these issues as part of trends, patterns and relationships, resist the temptation to explain and suggest reasons for these results because this discussion is more relevant to the concluding and evaluation sections.

PUTTING IT ALL TOGETHER

The sample experiment report below follows the ISMG criteria and may be used as a reference tool.

These are some sample calculations and analysis for the investigation in 1.10 Forming (an investigation into the relationship between pendulum length and period for a simple pendulum as a method of verifying the acceleration due to gravity).

Processed data and sample calculations

TABLE 4 Samples of the calculations used to process the data and associated uncertainties management

Calculation	Working
Length measurement uncertainty	0.005 per end, with two ends measured = ±0.01 m
Period measurement uncertainty	Reported accuracy of 25 milliseconds (Vernier, 2019), with two measurements required per time interval = ±0.05 s
Theoretical period	$T = 2\pi\sqrt{\frac{l}{g}}$ $= 2\pi\sqrt{\frac{0.365}{9.81}}$ $= 1.21\,\text{s}$
Average	$\text{average} = \frac{T1+T2+T3+T4+T5}{5}$ $= \frac{1.23+1.21+1.21+1.19+1.21}{5}$ $= 1.21\,\text{s}$
Trial uncertainty	$\text{uncertainty} = \frac{\text{max}-\text{min}}{2}$ $= \frac{1.23-1.19}{2}$ $= \pm 0.2$
Percentage uncertainty	$\text{percentage uncertainty} = \frac{\text{uncertainty}}{\text{average}} \times 100\%$ $= \frac{0.02}{1.21} \times 100\%$ $= 1.65\%$
Period-squared	$T^2 = 1.21^2$ $= 1.46\,\text{s}^2$
Period-squared propagated uncertainty	$1.46 \times \frac{0.05}{1.21} = \pm 0.06$
Gradient uncertainty	$\text{uncertainty} = \frac{\text{max}-\text{min}}{2}$ $= \frac{4.92-3.45}{2}$ $= \pm 0.74$
Gradient percentage uncertainty	$\frac{0.74}{4.10} \times 100 = 18.05\%$
Intercept uncertainty	$\text{uncertainty} = \frac{\text{max}-\text{min}}{2}$ $= \frac{0.28--0.43}{2}$ $= \pm 0.36$

Analysis

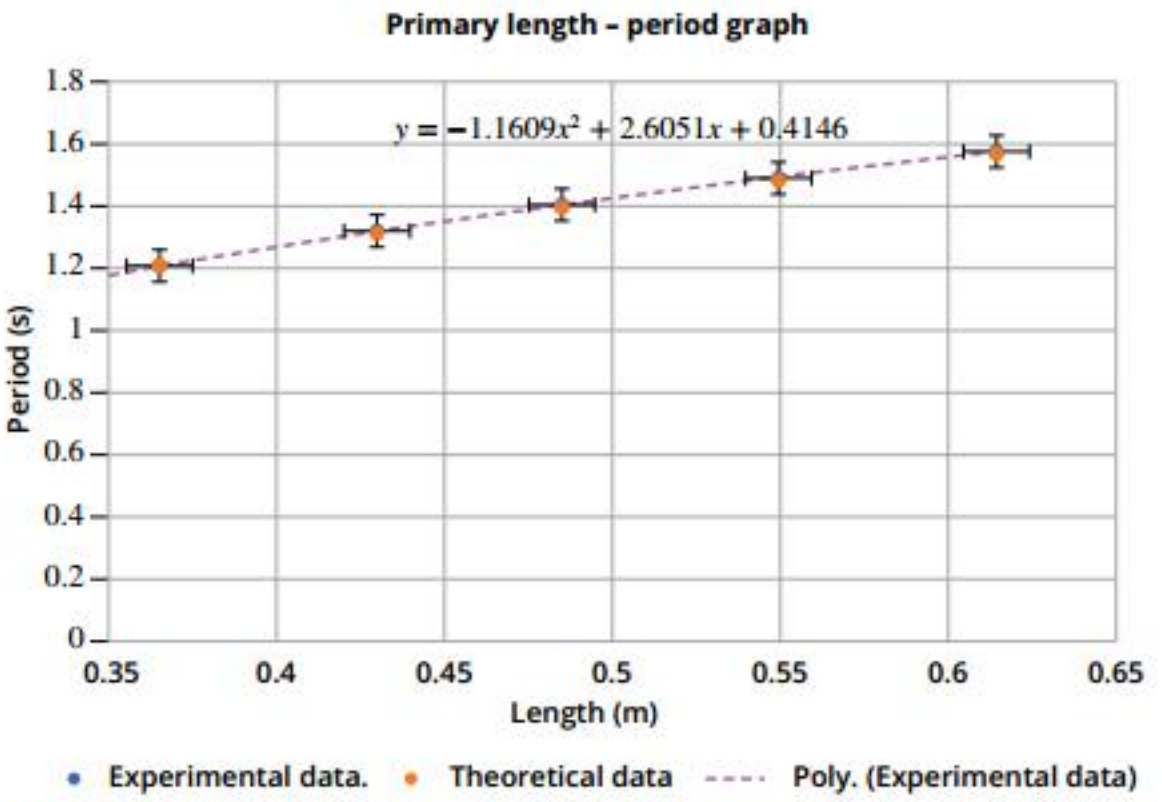


FIGURE 2 Primary graph showing experimental primary data and theoretical values

As the length of the string increases, the length of the period increases on a parabolic curve as expected, as the original relationship used to graph this includes a surd. According to Figure 2, a string of length 0.365 m produced a period time of 1.21 s, furthermore when the length of the string increased to 0.483 m, the period length also increased to 1.32 s and the rest of the data follows this trend. The dependent variable data has an uncertainty of ±0.05 as the measurement uncertainty was greater than the trial uncertainty. The theoretical and experimental data is very similar, though a small difference can be seen indicating there is some limiting factor effecting the results. To further verify the relationship, the relationship was linearised and a secondary graph was generated (Figure 3).

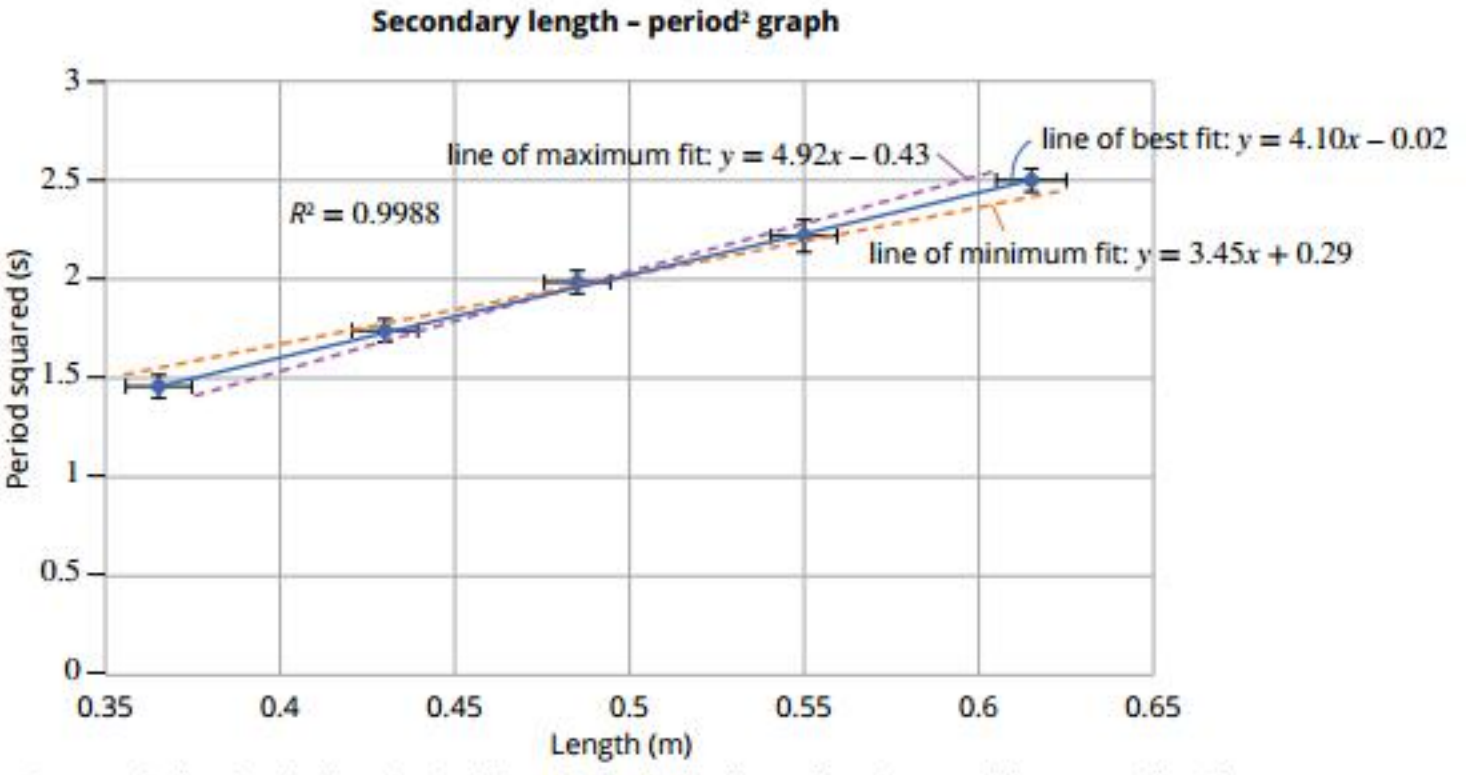


FIGURE 3 Secondary graph showing the linearised relationship, including lines of maximum, minimum, and best fit

The experimental linear relationship, including uncertainties was found to be:

$$T^2 = 4.10(\pm 0.74) \times l - 0.02(\pm 0.36)$$

This is consistent with the theoretical relationship of $T^2 \propto l$. The gradient is equal to $\frac{1}{g} \times 4\pi^2$ allowing for an experimental value of g to be determined:

$$4.10 = \frac{1}{g} \times 4\pi^2$$

$$g = 9.63 \text{ms}^{-2} \pm 18.05\%$$

$$g = 9.63 \text{ms}^{-2} \pm 1.74$$

The percentage error was determined by comparing the observed and expected values:

$$\text{percentage error} = \left| \frac{\text{measured} - \text{expected}}{\text{expected}} \right| \times 100$$

$$\text{percentage error} = \left| \frac{9.63 - 9.81}{9.81} \right| \times 100$$

$$= 1.83\%$$

This error is considerably smaller than the uncertainty of the gradient which supports the accuracy of the experiment, and the appropriateness of the theoretical relationship between period and length. This was further supported by the correlation coefficient R^2 having a value greater than 0.99, and the *y*-intercept being essentially zero, as expected from the theoretical relationship.

1.13 Interpreting and evaluating

Interpreting and evaluating requires a justified conclusion, justified discussion of the quality of the experimental process and suggestions for improvements and extensions derived on the analysis of the evidence.

JUSTIFIED CONCLUSION LINKED TO THE RESEARCH QUESTION

While you have already described the trend observed in the data (Analysis) it is important, in the conclusion, to extend this idea further to relate specifically to the research question. In an objective and clear manner, state the observed relationship between the dependent and independent variables using the terminology of the research question. Consider

- was the research question supported?
- has the research question been fully answered? If not, identify why not?

Table 1.13.1 shows examples of concluding statements.

TABLE 1.13.1 Strong and weak conclusions to a research question

Research question: How does the refractive index affect the angle of the refracted ray if the angle of incidence remains constant?	
Strong conclusion	**Weak conclusion**
Analysis of the results on the effect of an increase in refractive index showed an inverse linear relationship in which the sine of the angle of the refracted ray decreased from 0.57 to 0.44 as the refractive index increased from 1.3 to 1.6. These results support the expected theoretical relationship from Snell's law $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ where an increase in n_2 requires a proportional decrease in $\sin(\theta_2)$, given $n_1 \sin(\theta_1)$ remains constant.	The results show that increasing the refractive index caused the refracted angle to decrease.

There are several ways to justify the conclusion including but not limited to:

1. describing the physics concepts (scientific understanding and theory) that explains the observed relationship. Does the identified experimental relationship match the expected theoretical relationship? Is the expected theoretical value for the gradient/proportionality constant within the error bars of the experimentally determined value?
2. describing the evidence that led to the data trend. State values that indicate the strength of the relationship between the experimental variables (data, observations or results) including information gained from the errors bars on the graph, the R^2 value(s), the gradient and/or intercept uncertainty, and the percentage error. Refer to your tables/graphs to cite evidence.
3. comparing your finding to secondary data. This can be sourced from journal articles or other reliable sources that are directly connected to the experiment. Explain if the results support your observations. You should report that your results are consistent with the findings. Otherwise, it is essential that you reflect on the contrasting results and identify or suggest possible explanations why the results differ. This could be due to differences in the measurement technique or other factors such as the control or measured variables. It might also help you identify possible sources of error within your investigation.

In circumstances where a clear trend is not discernible, you can interpret what the results mean. Interpretations are made when limitations exist related to the methodology employed, the sample size, the instruments used, the variables controlled, and the raw data measured. Interpretations are not meant to provide answers and comprehensive explanations, only plausible causes of the limitations which may warrant further investigation.

In the conclusion, it is appropriate to briefly describe evidence relating to the quality of experimentation and any key limitations. You should address both reliability and validity (as described by % uncertainty and % error, respectively). Describe which of these was high/low and what this indicates about reliability and validity. Resist the temptation to explain these further as this is more usefully done in the Evaluation.

The conclusion is sometimes positioned after the analysis and sometimes at the end of the report. Its placement in your report will need to make sense to you and maintain the flow of ideas:

Option 1: planning → data collection and analysis → conclusion → evaluation

Option 2: planning → data collection and analysis → evaluation → conclusion

JUSTIFIED DISCUSSION OF RELIABILITY AND VALIDITY

Your analysis and conclusion have identified the trend in the data but also identified two other key aspects of the data – reliability and validity. A statement of these has also been made in the conclusion. The verb in analysis is 'identify' but here (in Interpreting and Evaluating) the cognition is 'discuss'. This means that you must explain statements made in the analysis related to % uncertainty (reliability) and % error (validity). In your discussion consider:

- are these low or high?
- what is the effect of these on the usefulness of the data to answer the research question? What could have caused excessive uncertainty and random error?
- what could have caused excessive systematic error?
- any factors that could affect the validity, accuracy, precision and reliability of data.

As you consider this discussion, remember that your data processing has provided extensive evidence – not just the independent-dependent variable relationship but also measurement uncertainty, uncertainty of the mean, gradient/proportionality constant, intercepts, and percentage error. Use these values to add depth to your discussion and use evidence rather than methodology to describe and discuss uncertainty and limitations in the investigation. For example, if you have calculated the percentage uncertainty associated with the measurement instrument (say, a measuring cylinder) to be 0.24% (see above) then suggesting that the lack of precision of this equipment is the cause of a percentage error of 40% is not reasonable.

A second example of the use of evidence relates to percentage error. If you have calculated the percentage error and have found that it increases throughout the experiment, your reasoning should relate to why this factor has increased. An example of this could be the components of an electrical circuit increasing in temperature the more the circuit is used. As a result, we expect the systematic error to increase during the experiment, and so percentage error should increase as well. Coverage of the impact of systematic and random errors on the data and results should be evident in your analysis for the characteristic of 'justified discussion of validity' to be met.

As you discuss factors affecting the quality of the data, remember the definitions of random and systematic error, and describe the factor in terms of one of these. Is the factor expected to always produce a change in the same direction (systematic error, low validity)? Or will the factor produce a more random effect where the value is sometimes higher and sometimes lower (random error, low reliability)? Look carefully at the evidence in your data for each of these. Refresh your understanding of random and systematic error using Figure 1.13.1.

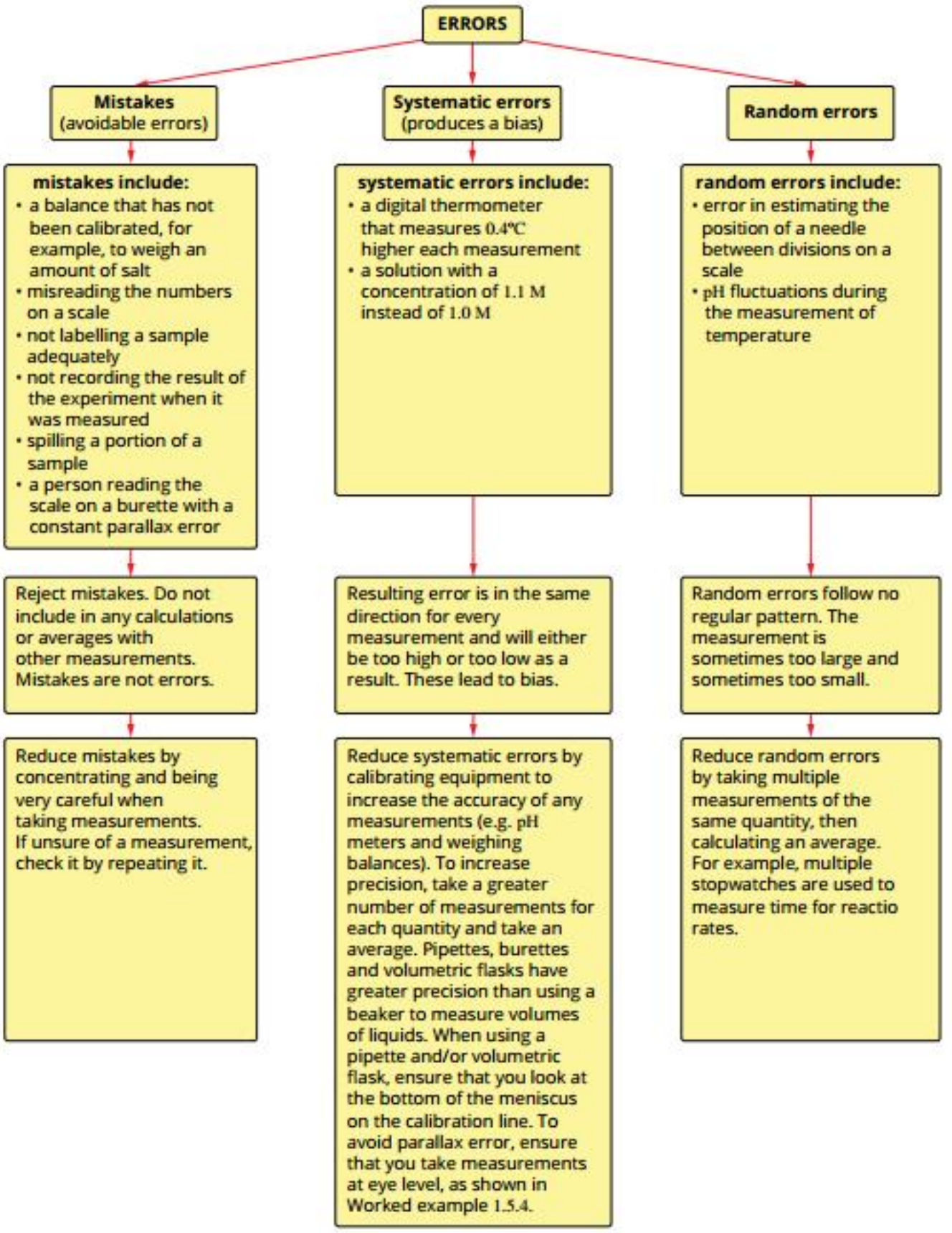

ERRORS
Mistakes
(avoidable errors)
Systematic errors
(produces a bias)
Random errors
mistakes include:
• a balance that has not been calibrated, for example, to weigh an amount of salt
• misreading the numbers on a scale
• not labelling a sample adequately
• not recording the result of the experiment when it was measured
• spilling a portion of a sample
• a person reading the scale on a burette with a constant parallax error
systematic errors include:
• a digital thermometer that measures 0.4°C higher each measurement
• a solution with a concentration of 1.1 M instead of 1.0 M
random errors include:
• error in estimating the position of a needle between divisions on a scale
• pH fluctuations during the measurement of temperature
Reject mistakes. Do not include in any calculations or averages with other measurements. Mistakes are not errors.
Resulting error is in the same direction for every measurement and will either be too high or too low as a result. These lead to bias.
Random errors follow no regular pattern. The measurement is sometimes too large and sometimes too small.
Reduce mistakes by concentrating and being very careful when taking measurements. If unsure of a measurement, check it by repeating it.
Reduce systematic errors by calibrating equipment to increase the accuracy of any measurements (e.g. pH meters and weighing balances). To increase precision, take a greater number of measurements for each quantity and take an average. Pipettes, burettes and volumetric flasks have greater precision than using a beaker to measure volumes of liquids. When using a pipette and/or volumetric flask, ensure that you look at the bottom of the meniscus on the calibration line. To avoid parallax error, ensure that you take measurements at eye level, as shown in Worked example 1.5.4.
Reduce random errors by taking multiple measurements of the same quantity, then calculating an average. For example, multiple stopwatches are used to measure time for reactio rates.

FIGURE 1.13.1 Types of errors that can be made in an experiment

One form of systematic error is **bias** in sampling or measurements. Bias can result from poor definitions, incorrect assumptions, misunderstandings between group members and failure to use equipment correctly. Some biases cannot be eliminated but should at least be addressed in the discussion.

IDENTIFY IMPROVEMENTS AND EXTENSIONS

Once any limitations or problems in the methodology have been identified, recommend improvements for how the investigation could be conducted if repeated. Some guiding questions are:

- has my research question been fully answered and what evidence is further required to answer it?
- what improvements can be made to aspects of the investigation identified as limitations?
- what changes to the materials or method would address the lack of reliability or validity of the data?

Questions to consider when suggesting extensions to this student experiment could include

- do the findings lead to further questions?
- can the findings be extended to another situation?
- what extensions can be investigated for a related scientific idea?

In the modifications section, you provided a reason for each change that you made to the original experiment. In a similar way, provide a reason for each improvement and extension. In order to demonstrate that the extensions are logically derived from the analysis of the evidence, you need to provide a reason for each extension and how it relates to the evidence. Similarly, how the suggested improvements would have addressed or overcome the limitations that were identified earlier. Statements such as 'test more substances' or 'complete more trials' do not match a high-level response ('logically derived' ISMG descriptor) and will better match lower descriptors ('related' or 'ineffective').

The syllabus descriptor states 'logically derived' and so it is important to limit your suggestions for improvements and extensions to experimental issues that have already been identified (in analysis and evaluation). Conversely, if you have described a key limitation of the experiment related to high levels of random or systematic error, you should describe improvement(s) for this issue.

PUTTING IT ALL TOGETHER

The sample experiment report below follows the ISMG criteria and may be used as a reference tool for interpreting and evaluating.

This is a conclusion and evaluation of the investigation in 1.10 Forming (an investigation into the relationship between pendulum length and period for a simple pendulum as a method of verifying the acceleration due to gravity).

Conclusion and Evaluation

The experimental percentage error of 1.83% was a significant improvement on the original experiment, suggesting the modifications did indeed improve reliability. The presence of the expected value of $9.81 ms^{-2}$ within the experimental uncertainty of $9.63 ms^{-2} \pm 1.74$ suggests the experiment was valid. Regardless, the experiment was still inaccurate, as the experimental value of $9.63 ms^{-2}$ was lower than the theoretical value. Conversely, precision was extremely high, with the absolute uncertainty being lower than the measurement uncertainty for the data trials. This could suggest the presence of random error, though the R^2 value being greater than 0.99 suggests this is unlikely to be the case. Additionally, the negligible *y*-intercept of –0.02 does not suggest the presence of a systematic error.

The uncertainty in the independent variable contributed more to the overall uncertainty than the dependent variable. This is because the photogates are very precise (Vernier reports a maximum uncertainty of 25 ms) and automatic, removing random human error. However, the length of the pendulum was still measured manually using a meter ruler, and introduced a limitation in the form of measurement uncertainty at both ends of the tape measure. This measurement was taken in the air after the pendulum had been mounted to remove the random error which could be introduced to the length if it was measured before being mounted in the pendulum. This does however introduce the possibility of random errors if the ruler and string were out of alignment due to being held unsteadily in the air without any sort of clamp or guide to read the value accurately. It is possible this resulted in the measurement error being higher than the values reported and may represent a significant limitation (see Table 5).

TABLE 5 Improvements

Improvements	Justification
Replace the ruler with a more precise device such as a laser measuring device.	The ruler was the main source of measurement uncertainty. Implementing this modification will improve precision and increase reliability.
Fix the ruler to the table to ensure vertical alignment between pendulum and ruler.	This would reduce the uncertainty when reading the value off the ruler and increase accuracy of the measured length of the string.
Measure the angle of the string more closely rather than estimating.	This improves validity as ensuring the angle of the string is not be larger than 15° reduces other forces on the motion of the pendulum

The lower experimental value of g suggests the presence of a force opposing the motion of the pendulum. It is unlikely this is in the form of air resistance on the bob as the modifications made to the experiment were specifically chosen to limit this. Redirecting the experiment from freefall to a pendulum did however introduce a string. The ideal model of the simple pendulum uses a massless frictionless string. The presence of air resistance on the string, plus frictional forces at the pivot point of the pendulum are likely sources of these forces opposing the motion of the pendulum and are excellent candidates for further experimentation (see Table 6).

The motion of a pendulum should be independent of angle, especially if the angle is kept beneath 15 degrees to limit other forces on the bob (The Physics Classroom, 2023). Admittedly, this meant we did not measure the angle of the string but just estimated it each time. If this estimation was poor, additional forces may have been present which would contribute to random error. Furthermore, a difference in predicted gravity could be due to the location of the experiment; gravitational acceleration is not the same globally as detailed in the rationale. While this may have had some impact, it is unlikely to be as low as $9.63\,m\,s^{-2}$.

TABLE 6 Extensions

Extensions	Justification
Investigate the relationship between period and angle.	When the angle is greater than 15°, the formula becomes much more complex as more forces are acting on it. This would allow for a greater understanding of the relationship between these variables and would confirm if this contributed to inaccuracy in this experiment.
Investigate the use of different types of string	This would provide evidence for the impact of the motion of the string on the motion of the bob and would allow us to determine if forces on the string contributed to the lower experimental value for gravity.

Conclusion

From the data collected, a conclusive answer for the research question has been determined. The results lead to the conclusion that increasing the length of the string will increase the square of the period. The relationship found within the experiment was:

$$T^2 = 4.10(\pm 0.74) \times l - 0.02(\pm 0.36)$$

This supports the theoretical proportionality of $T^2 \propto l$. The results were deemed to be reliable as despite a percentage uncertainty in the gradient of 18.05%, the percentage error was only 1.83% and the R^2 value was greater than 0.99 suggesting limited influence of random error. The presence of the expected value of $9.81\,m\,s^{-2}$ within the experimental uncertainty of $9.63\,m\,s^{-2} \pm 1.74$ suggests the experiment was valid. The inaccuracy of the experimental value, particularly with the value being lower than expected, suggests the presence of additional forces on the pendulum providing an avenue for further research to investigate the impact of these limitations.

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WDC for Geophysics, Beijing. (2015). *Gravity of Earth.* Retrieved from WDC for Geophysics, Beijing: http://www.geophys.ac.cn/infowin/Gravity.asp#:~:text=It%20has%20an%20approximate%20value,ft)%20per%20second%20every%20second.

1.14 Syllabus requirements

The research investigation assessment requires students to investigate a claim, provided by their teacher, by drawing on secondary evidence from scientific texts. Students will draw on research to analyse, interpret and evaluate the evidence to reach a justifiable conclusion about the research question. The task requires students to locate and use information beyond the scope of their knowledge and data they have been given.

QCAA Syllabus states that students must work individually to develop and investigate their own research question.

The research investigation constitutes 20% of the total subject score and may be presented in:

- written form of up to 2000 words, or
- multimodal form using at least two modes delivered simultaneously and up to 11 minutes.

INSTRUMENT-SPECIFIC MARKING GUIDE

As with the Student experiment, responses are assessed against an instrument-specific marking guide (ISMG). In developing the research report, it is important to keep in mind the assessment objectives, particularly the characteristics that are described in the performance level descriptors.

- The ISMG has four criteria:
  - Forming and finding
  - Analysing
  - Interpreting
  - Evaluating

Each criterion has performance levels, against which the qualities of the response are assessed.

A performance level is comprised of a performance level descriptor and mark (or range of marks).

The performance level descriptor describes the characteristics that are demonstrated by a response of that quality.

Each stage of the development of the research investigation will be discussed and aligned with the relevant ISMG criteria, and elaborations for the highest performances.

The ISMG criteria and elaborations of each are shown in Table 1.14.1, for the highest performances.

Note that in Year 11, this internal assessment task will align with Unit 2 Linear motion and waves and not Unit 4 Revolutions in modern physics. A research project based on IA3, but undertaken in Year 11, may require some modification of assessment objectives to relate to Unit 2 subject matter.

TABLE 1.14.1 Alignment of syllabus criteria, objectives, descriptors and marks with the modules of Part B

Criteria	Assessment objectives	Instrument specific marking guide (ISMG) descriptors – Criteria are demonstrated by:	Marks	Module
Forming and finding	1 Describe ideas and findings about special relativity, quantum theory or the Standard Model. 6 Investigate phenomena associated with special relativity, quantum theory or the Standard Model through research.	• a considered rationale identifying clear development of the research question from the claim • a specific and relevant research question • selection of sufficient and relevant resources • appropriate use of genre conventions • acknowledgement of sources of information through appropriate use of referencing conventions	5	1.15 1.8
Analysing	3 Analyse research data about special relativity, quantum theory or the Standard Model.	• the identification of sufficient and relevant evidence • thorough identification of relevant trends/patterns/relationships in evidence • thorough and appropriate identification of limitations of evidence	5	1.16
Interpreting	1 Describe ideas and findings about special relativity, quantum theory or the Standard Model. 4 Interpret research evidence about special relativity, quantum theory or the Standard Model.	• justified scientific argument/s • justified conclusion linked to the research question • fluent and concise use of scientific language/representations	5	1.17 1.8
Evaluating	5 Evaluate research processes, claims and conclusions about special relativity, quantum theory or the Standard Model.	• justified discussion of the quality of evidence • extrapolation of credible findings of the research to the claim • suggested improvements and extensions to the investigation that are considered relevant to the claim	5	1.18
Total			20	

The final report for the student experiment may be organised under the criteria headings in the instrument-specific marking guide (ISMG): forming, finding, analysing and interpreting and evaluating. However, this is not mandated, and you may elect to organise your report in a different but logical order using alternate headings.

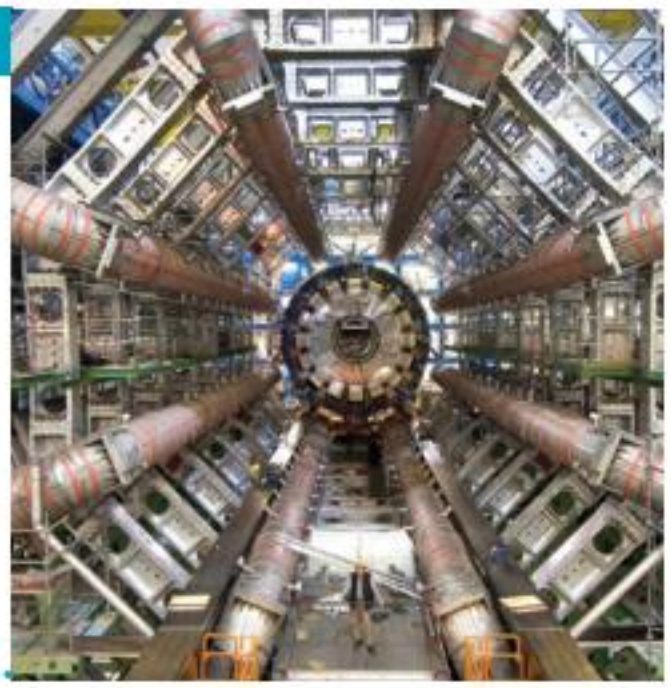
Note that items such as title or contents pages, the abstract, appendixes, bibliography or reference list, and in-text references are not included in the word count. The contents of the appendix are not used for determining levels of achievement.

The research question should specifically address one of the concepts associated with the claim. Commence by identifying a claim and developing your own research question based on that claim. Since this assessment relies heavily on access to research, students need to be able to easily find sources relevant to the research question. Throughout the process be mindful that scientific language and representations are used. (Refer to Module 1.8).

1.15 Forming and finding

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand and select a claim
- classify elements of the claim
- unpack the elements to identify variables, terms and concepts related to the claim
- plan research and locate sources relevant to the claim
- distinguish between primary and secondary sources
- locate a range of primary and secondary sources
- use a scientific journal to record the information in the sources
- refine the concepts to develop an investigable research question
- understand the criteria against which the research investigation will be assessed.



The ISMG for the Forming and finding criterion is assessed in relation to the development of the research question from the claim and the communication of the findings of the investigation through a scientific report.

There are three aspects to the Forming and finding criterion.

To achieve the highest mark (5) in the Forming and finding criterion you need to create a specific research question. One way to do this is to clearly link to the subject matter in a way that identifies measurable independent and dependent variables, as well as any relevant controlled variables. Then you need to construct a rationale that clearly outlines how the research question is developed from the original claim. A research rationale outlines the reason to conduct research on your chosen claim, i.e. it is the justification for the investigation. This is achieved by conducting a thorough literature review to understand what is already known in the chosen topic and to identify the concepts from Unit 4 that are related to the topic. Students who explain concepts outside the syllabus in their Rationale struggle to stay within the word limit.

Finally, the structure and style of the report, quality of sources and use of referencing are assessed.

UNDERSTANDING THE NATURE OF A CLAIM

A claim is an assertion made without any accompanying evidence to support it. The claim can be a sentence, statement within a sentence, title of an article, quote or anything published in any form. The claim should be in isolation from any justification using data, research, evidence or reasoning from known information to support it. The claim is a broad statement that can encompasses a range of related topics and relationships.

SELECTING A CLAIM

If you are provided with a choice of claims, you should ask yourself the following questions about the claims.

Which claims:

- interest me or are most relevant to me?
- will have secondary evidence available to me?
- are easy to break down and link to the subject matter in the unit?
- are broad enough to allow me to undertake a unique investigation?

The answers to these questions will help you decide on the most appropriate claim for you.

To develop the research question from a claim students must analyse, understand and identify one or more of the following:

- known scientific concepts
- variables
- measurable terms
- ideas related to concepts
- a term that is stated to influence another.

Record the information you collect, your thoughts and analysis in a hard copy or electronic scientific journal. When you write the report, this information will be useful in writing the rationale that documents how the research question was developed from the claim. Write down all the elements found in the claim and try to categorise them using the list above. Each element within the claim may suit more than one category. Table 1.15.1 outlines two examples of analysing and categorising elements of a claim.

TABLE 1.15.1 Two examples of analysing and classifying elements of a claim

Example Claim 1: Cold fusion could provide a limitless supply of energy to the world		
Elements	**Classifying elements of the claim**	**Unpacking the elements**
Nuclear fusion	known scientific concepts	source of energy created when smaller nuclei collide and join to make a heavier nucleus
	ideas related to concepts	limited success implementing controlled artificial fusion
Energy production	measurable terms variables	produces energy from matter via $\Delta E = \Delta mc^2$
	ideas related to concepts measurable terms	utilisation of the energy within the grid
	ideas related to concepts measurable terms	efficiency of the energy source: energy required compared to energy produced
Define the term 'limitless'	a term that is stated to influence another. measurable terms	abundance of fuel
	a term that is stated to influence another. measurable terms	amount of waste generated
Explain the significance of 'cold' in this context	known scientific concepts measurable terms	fusion requires high temperature and pressure to start and sustain the atoms must have enough energy to overcome the electrostatic repulsion of the protons in their nuclei achieving fusion at low temperature has not yet been achieved
	known scientific concepts variables	Heat engines require a heat source and a cold sink

Example Claim 2: Photons are a better source of fuel than atoms		
Elements	**Classifying elements of the claim**	**Unpacking the elements**
Photons	known scientific concepts	quantised packets of energy
	ideas related to concepts	does not require a medium
Fuel	ideas related to concepts	mechanism of energy production
	ideas related to concepts measurable terms	abundance and ease of utilisation
Define the term 'better'.	a term that is stated to influence another measurable terms	efficiency
	a term that is stated to influence another ideas related to concepts	photons are massless

Elements	Classifying elements of the claim	Unpacking the elements
Applications	known scientific concepts	propulsion – solar sails
	known scientific concepts	generation – solar cells
	known scientific concepts	storage – batteries

LOCATING SOURCES

It is important to recognise that this is not a university quality report as students do not have the time, access or understanding to analyse the information provided in scientific research journals. In addition, the research investigation is limited to 2000 words so does not allow for the depth of investigation in a research journal.

When gathering scientific evidence for the research investigation, source it from reputable publications including:

- scientific journals: research papers and scientific reviews
- scientific articles written by organisations who apply scientific research to their industry
- commercial articles such as science magazines, newspapers and also websites.

The research investigation must include a reference list of sufficient and relevant sources. *Sufficient* means 'enough or adequate for the purpose', and *relevant* as 'bearing upon or connected with the matter in hand; to the purpose; pertinent; applicable and pertinent; has direct bearing on'. Figure 1.15.1 points out the features of sources deemed *sufficient* and *relevant*.

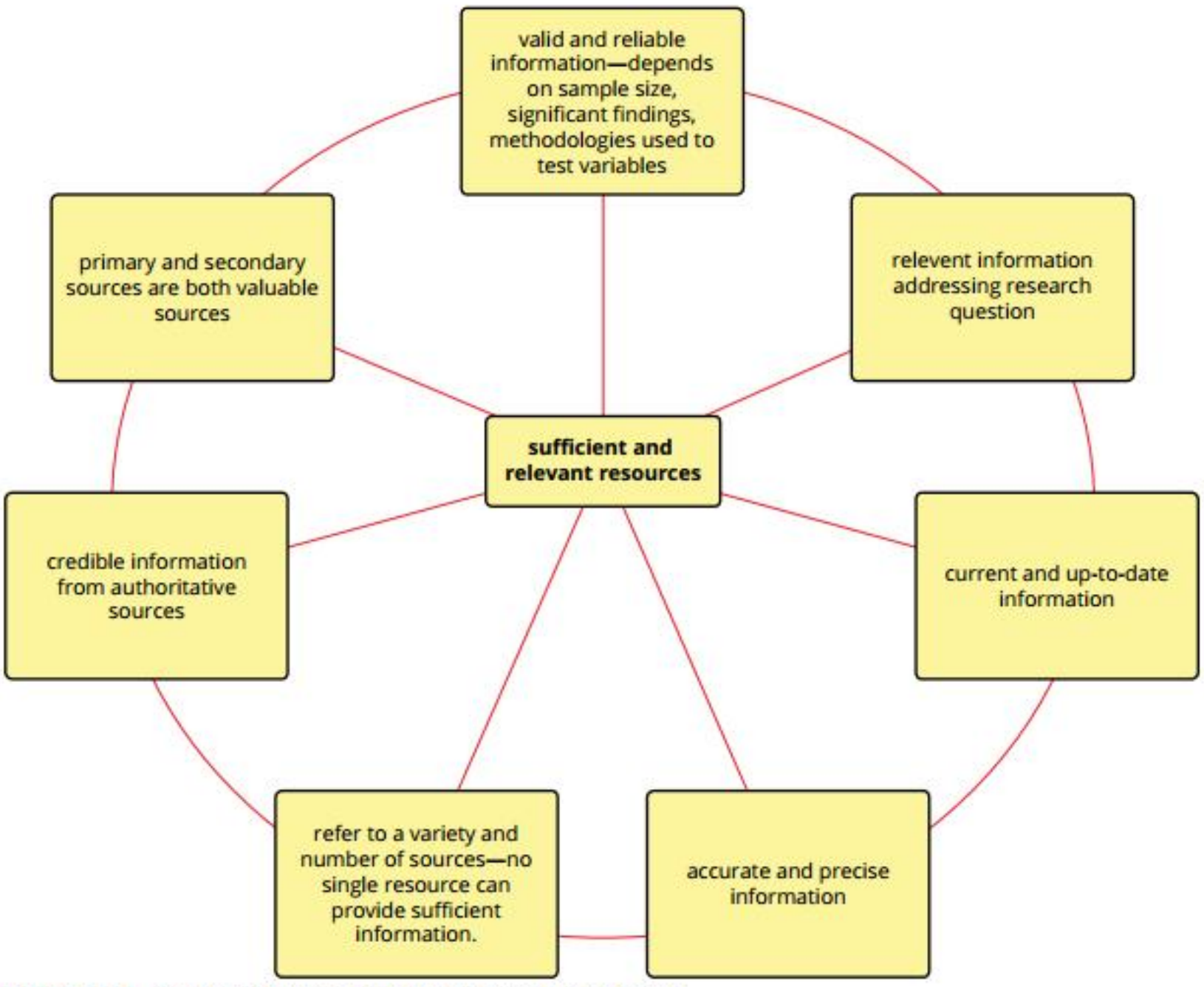

valid and reliable information—depends on sample size, significant findings, methodologies used to test variables
primary and secondary sources are both valuable sources
relevent information addressing research question
sufficient and relevant resources
credible information from authoritative sources
current and up-to-date information
refer to a variety and number of sources—no single resource can provide sufficient information.
accurate and precise information

FIGURE 1.15.1 Features of sources suitable for the research investigation

A good place to start research is to look for interesting sites and textbooks to identify relevant keywords and concepts rather than immediately searching for complex research articles. This could include videos, general scientific articles and even Wikipedia to gain a general understanding of the topic.

Access available open-access sources, some of which can be identified using educational, government or industry websites, with suffixes including .edu .gov or .org. There are academic search engines such Google Scholar and Semantic Scholar. Be aware that both of these use AI to search for your requested articles and that may involve some bias. However, this does not mean the article itself is AI-generated.

Where necessary, you can often freely access scientific journals through academic networks, such as ResearchGate and Academic.edu. If the article has not already been published, you can request a copy of the article from the author or ask them a question. You school librarian can help here.

When accessing the sources start with the title, which should include some of the keywords related to the concept. As you refine the focus of your investigation use the evidence to refine the claim and develop the rationale. Your search will narrow and lead to data tables, graphs, images and abstracts. If the abstract is useful, download the article or request a copy of it. Look at the images and conclusion. These may be more useful than the text of the article.

Remember to document the sources and summarise the information contained in your journal to facilitate the writing of the report and generate a reference list. Some sources provide help with the citation of scientific articles.

A useful way to collate the evidence is in a table with headings such as:

- Article overview, which summarises the article
- Evidence, which outlines the methodology, trends/patterns/relationships and limitations
- Conclusions, which summarises the evidence
- Relationship to research question, which includes your thoughts and highlights the parts of the research question that this evidence addresses
- Limitations, which identifies aspects of the research question that are not addressed or cannot be answered due to the methodology
- Source- primary/secondary/reference/website (consider whether the information you use is from a primary or secondary source).

Primary and secondary sources

Table 1.15.2 summarises the characteristics of primary and secondary sources. Sometimes the same information may be contained within a primary and a secondary source, depending on when and by whom it was written. For example, a scientist's journal article on a clinical trial of treatments for teenage obesity is a **primary source**, while a general magazine article about teenage obesity, written by a journalist and referring to the scientific study, is a **secondary source**.

TABLE 1.15.2 Summary of primary and secondary sources

	Primary sources	Secondary sources
characteristics	first-hand records of events, experiences, experimental data written at the time the event happened original documents	interpretations of primary sources written by people who did not see or experience the event use information from original documents but rework it
examples	results of experiments scientific journal/magazine articles reports of scientific discoveries photographs, specimens, maps and artefacts interviews with experts websites (if they meet the criteria above)	textbooks biographies newspaper articles magazine articles radio and television documentaries websites that interpret the scientific work of others podcasts

A primary source is written by the observer/witness of an event or the scientist who conducted the research. The information has only been processed by the original observer, therefore it is the least biased of all available sources of information. However, even primary sources may be biased, as the observer or researcher had to make choices related to the observation, control of variables, use of instruments and choices for processing data.

Secondary sources of information are not eyewitness accounts but interpretations of events by other people. As second-hand information, the accuracy and reliability may be reduced, and events may be interpreted through the writer's perception and bias, and there may be ommissions or material taken out of context. You should aim to use a wide range of data sources when using secondary data, to cross-check for accuracy, reliability and validity of information. A single source will not be accepted as 'sufficient'.

When searching for information and evidence, follow these guidelines.

1 Determine if it is a primary or secondary resource.
2 Confirm that it is valid.
   - **a** Check that it contains information that is specifically related to the claim.
   - **b** Check the evidence and information is pertinent to the variables in the research question.
3 Assess its reliability.
   - **a** Is it current/recent information?
   - **b** Is it up-to-date in its understanding of relationships?
   - **c** Is the evidence equivalent to other sources?
   - **d** Check credibility—consider who the author is, their qualifications and expertise.
   - **e** Evaluate the methodology, including what variables were controlled or measured.

Articles in scientific journals

Peer-reviewed scientific journals are excellent sources of information. They are usually focused on one area of science with a collection of scientific reports written by scientists who conducted research. The reports and articles found in scientific journals are published primary sources, meaning they are the results of the experiments (Figure 1.15.2 on page e125).

Mitigating Temporal Fragility in the XY Surface Code

Pei-Kai Tsai,[1,2] Yue Wu,[2,3] and Shruti Puri[1,2]

[1]*Department of Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Yale Quantum Institute, Yale University, New Haven, Connecticut 06511, USA*
[3]*Department of Computer Science, Yale University, New Haven, Connecticut 06520, USA*

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An important outstanding challenge that must be overcome in order to fully utilize the XY surface code for correcting biased Pauli noise is the phenomenon of fragile temporal boundaries that arises during the standard logical state-preparation and measurement protocols. To address this challenge we propose a new logical state-preparation protocol based on locally entangling qubits into small Greenberger-Horne-Zeilinger-like states prior to making the stabilizer measurements that place them in the XY-code state. We prove that in this new procedure $O(\sqrt{n})$ high-rate errors along a single lattice boundary can cause a logical failure, leading to an almost quadratic reduction in the number of fault configurations compared to the standard state-preparation approach. Moreover, the code becomes equivalent to a repetition code for high-rate errors, guaranteeing a 50% code-capacity threshold during state preparation for infinitely biased noise. With a simple matching decoder we confirm that our preparation protocol outperforms the standard protocol in terms of both threshold and logical error rate in the fault-tolerant regime where measurements are unreliable and at experimentally realistic biases. We also discuss how our state-preparation protocol can be inverted for similar fragile-boundary-mitigated logical-state measurement.

DOI: 10.1103/PhysRevX.14.031003 Subject Areas: Quantum Information

I. INTRODUCTION

Fault-tolerant, scalable quantum computation with noisy physical hardware relies on encoding quantum information in a large number of physical qubits making up an error correcting code. Two important performance metrics for an error correcting code are its threshold, which is the physical error rate below which error correction becomes successful, and the amount of error suppression possible for a given number of qubits. These depend on its *distance* which sets the minimum weight of an uncorrectable error, the number of fault configurations leading to uncorrectable errors, and their likelihood which heavily depends on the details of underlying noise model [1,2].

Biased-Pauli noise is a common noise model describing many practical qubit architectures in which errors that cause bit flips are far less likely than those that only lead to phase flips [3–10]. When only phase-flip noise is present, we say that the noise is infinitely biased. The discovery of native bias-preserving controlled-NOT gates [9–13] has driven research toward tailoring codes to be highly effective at correcting biased-Pauli noise [14–29]. Two leading candidates for such codes are the XY surface code [19] and XZZX surface code [23]. These are obtained from the standard CSS surface code which consists of X- and Z-type stabilizers by local Clifford deformation of its stabilizers [30]. Their favorable properties arise from the underlying symmetry of their stabilizers due to which these codes reduce to repetition codes when noise is infinitely biased (see Ref. [31] for further discussion on the role of symmetries in error correction). Thus, these codes have a 50% threshold at infinite bias. Moreover, compared to the planar XZZX surface code, the XY code can also tolerate quadratically higher weight phase errors, making it more desirable for correcting strongly biased noise.

It is natural to ask if the favorable properties of the XY code persist during logical state preparation, which is the very first step in any quantum algorithm. In the standard approach, a logical X state $|+_L\rangle$ is prepared by initializing each physical qubit in the $|+\rangle$ state, followed by a measurement of all the code stabilizers. However, in this process half of the stabilizers cannot be used for detecting phase errors, destroying the symmetry of the XY code, a phenomenon that has been referred to as *temporal fragile boundaries* [32,33]. As a consequence, the code does not reduce to a repetition code under pure phase noise and, as we will show, the threshold at infinite bias degrades to ~11%. Moreover, during state preparation the code distance to phase errors scales as $\sqrt{n}$, where n is the number of physical qubits of the code. In contrast, if all the stabilizers

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FIGURE 1.15.2 An extract of an article in a scientific journal of a research report written by scientists. It is strictly structured with a pertinent title, names of authors, an abstract, the report using the convention of: introduction, method, results, analysis, conclusion and ends with a reference list.

Access to scientific journals can be difficult as many journals require you to purchase a subscription or membership, though some are free. Figure 1.15.3 provides ideas for accessing scientific journals.

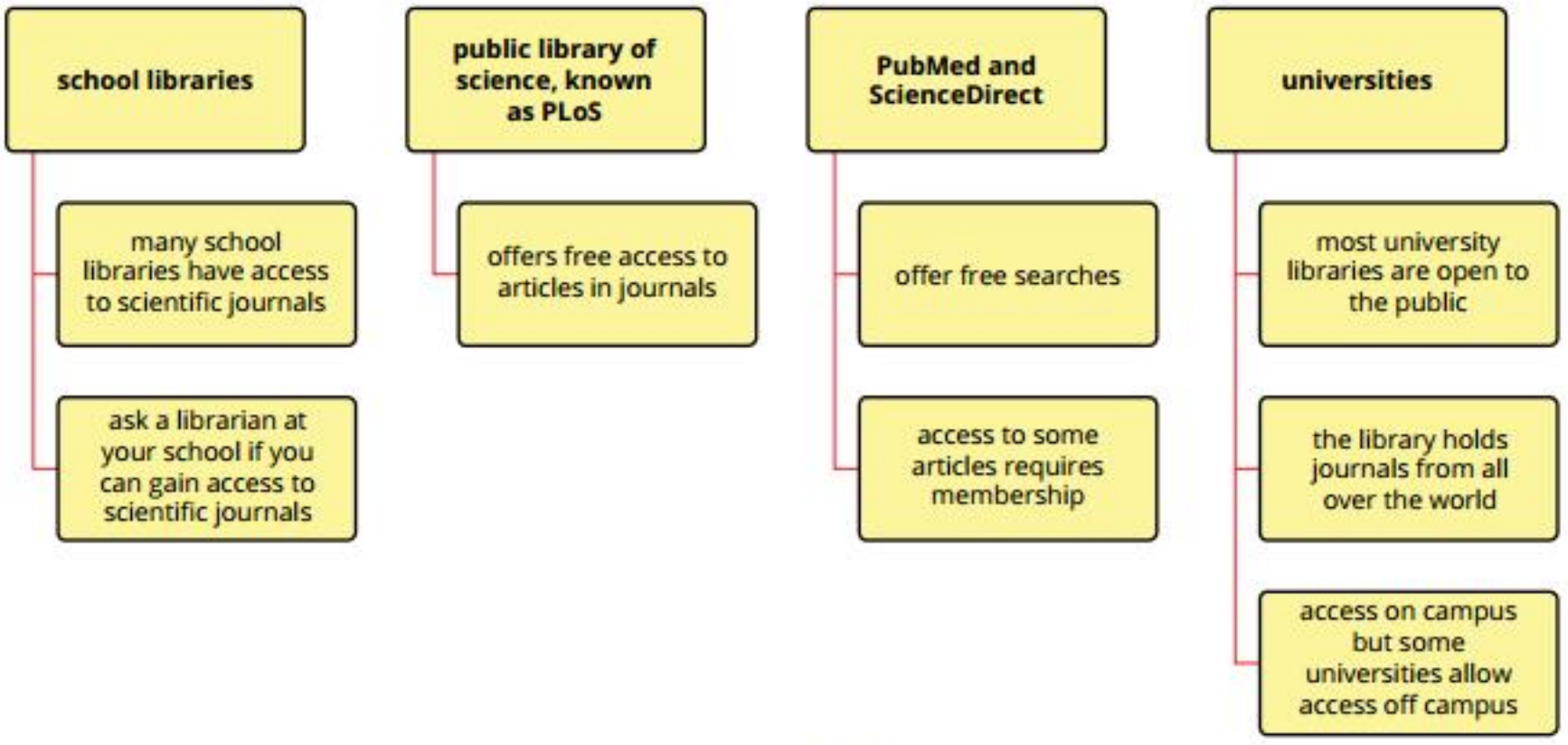
school libraries
many school libraries have access to scientific journals
ask a librarian at your school if you can gain access to scientific journals
public library of science, known as PLoS
offers free access to articles in journals
PubMed and ScienceDirect
offer free searches
access to some articles requires membership
universities
most university libraries are open to the public
the library holds journals from all over the world
access on campus but some universities allow access off campus

FIGURE 1.15.3 Suggestions and information on accessing scientific journal articles

Scientific articles are excellent sources of information, but also have their drawbacks as sources for the research investigation. Table 1.15.3 outlines some advantages and disadvantages of sourcing and using articles in scientific journals for the research investigation.

TABLE 1.13.3 Advantages and disadvantages of scientific articles

Advantages	Disadvantages
• written by experts • authoritative information (peer-reviewed) • most current information • logical, organised layout • content is relevant to the topic • contains an abstract that summarises all information in the article and saves you reading time. (If you don't find the information in the abstract, the article is not relevant.) • primary source • provides introductory comments that review the literature of the field and position of the research focus of the article in it.	• information is complex and challenging to understand • complex language and advanced processing and analysis of data • requires a high level of scientific literacy, language and numeracy to understand • may be time consuming to read and analyse • well established concepts do not have recent published articles • may be difficult to locate and gain free access to

Books and physical publications

Secondary sources such as good science magazines and books are valuable sources of secondary information.

The first source you should use is your textbook. The language and concepts are presented specifically for high school students and have been carefully reviewed for accuracy. In addition, the textbook addresses the syllabus objectives. Non-fiction books and magazines will probably be commonly used resources for the research investigation. Common commercial science magazines you might find in your school library include *Double Helix*, *Cosmos*, *Scientific American* and *New Scientist* (Figure 1.15.4). Table 1.15.4 on page e126 outlines some advantages and disadvantages of non-fiction books as sources for your research.

FIGURE 1.15.4 A science magazine you might find in your school library

TABLE 1.15.4 Advantages and disadvantages of book resources

Advantages	Disadvantages
• may be written by experts • potentially authoritative information • logical, organised layout • content is relevant to the topic • contain table of contents and index to help find relevant information • easily located in libraries • written in language that is understandable	• may not have been published recently • usable by only one person at a time • may have more bias than primary sources

Searching online

Online sources include online scientific organisations such as CSIRO, NCBI, AIMS, Bioscience (Oxford Academic) and other university publications and press. Many government and privately funded science organisations publish material, along with not-for-profit scientific organisations. Websites may direct you to magazines and scientific journals, such as those described above, the news, podcasts, blogs and videos (institutional, company and personal).

Information located on the internet requires very careful scrutiny. The openness and ease of publishing on the internet, means information may not be valid and reliable. Use the earlier guidelines to help you evaluate sources. Table 1.15.5 outlines advantages and disadvantages of locating and using information online.

When searching for relevant information, you need appropriate search terms to enter into a search engine. These tips can help your search.

- Break your search statement into concepts and key words.
- Find synonyms, other related terms and concepts that apply to the topic.
- Create concepts of 1–3 words to enter into the search engine.
- Try different combinations of terms.
- Do not settle for the first sites on the list or your first attempt; look beyond the first page of results.
- Look through the results for sites from science organisations and research institutions (e.g. CSIRO, WEHI, NIH; .gov, .org), universities (.edu) and science journals and magazines.

TABLE 1.15.5 Advantages and disadvantages of internet resources

Advantages	Disadvantages
• quick and easy to access to a range of sources • allows access to hard-to-find information • access to the whole world; millions of websites • information is potentially more up to-date • may be interactive and use animations to enhance understanding • choice of text-based material or images and videos to suit different learning styles	• may not be reliable, valid or credible • can easily side track with non-relevant information • a lot of 'junk' sites and potentially more biased material that may be out of context or unedited • need to discern search engine results to find most useful sites • cannot always tell how up-to-date information is or where it comes from • can be hard to tell who has responsibility for authorship • information may not be well ordered • often is not the original source

Overview of resources

Your textbook should be your first source of reliable information. Other information should be consistent with this. Articles published in journals and magazines often present findings of new research, which may or may not be confirmed later, so be careful not to treat such sources of information as established fact. Scientific journals are **peer-reviewed** (critically reviewed by other specialist scientists), which gives them more credibility than other sources.

However, it is important that the sources utilised in the investigations are credible and easily accessible.

FORMING A QUESTION

The claim is used to develop the research question investigated in the assessment. The variables inferred in the claim may not be measurable or directly observable, and therefore they may not be scientific.

To help to develop the research question, break the claim into possible scientific elements, each of which could be used to form a question (Table 1.15.6 on page e128). Separating the claim into elements, such as related terms and concepts, enables you to formulate variables, measurable items and questions. Thus you can identify scientific elements of the claim that are contained in the syllabus.

Based on these elements formulate a number of questions related to the claim and record all in the journal. The research question must specify a dependent variable and enable a response that will evaluate the validity or the reliability of the claim. You will need to understand the dependent and independent variables, and the relationship between the variables. The research question must identify the dependent variable and may also specify the independent variable.

Some guidelines to help form a research question include:

- identifying a dependent variable that can be linked to the claim or rephrasing the claim into something measurable.
- developing an element of the claim into the independent variable or identifying it in the stimulus material.
- phrasing a question to ask if the independent variable will influence, cause or correlate with the dependent variable.
- writing a few different questions.

Usually, the questions improve as you write more, which allows the formulation of a more developed research question. At this stage these questions can still be quite broad but as they are refined the focus of the research question needs to be very narrow so that the research report can be completed within the assessment conditions.

The process to developing a research question is often cyclical (Figure 1.15.5).

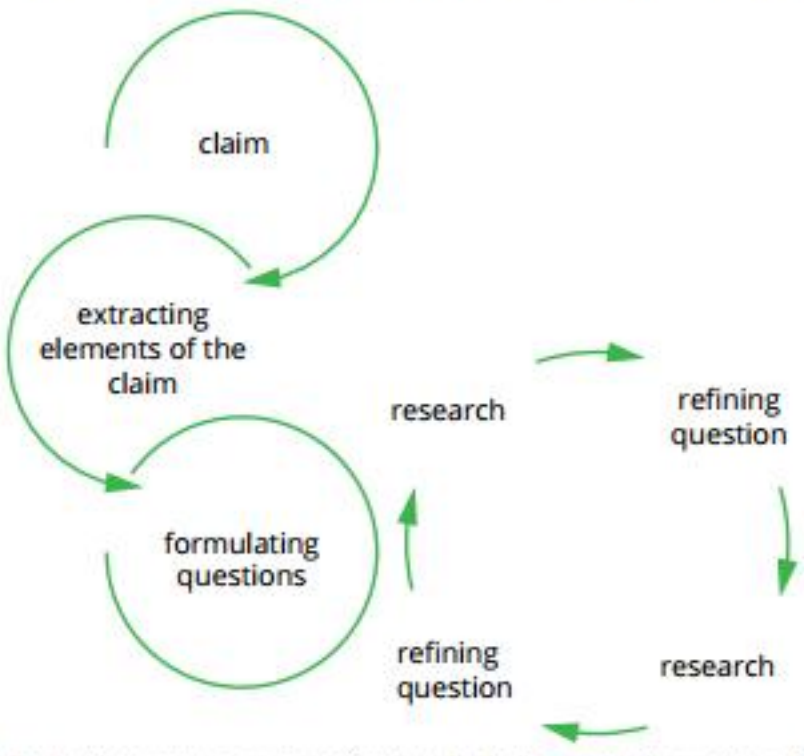

FIGURE 1.15.5 A chart of a common process for developing a research question. This cycle can be repeated as many times as necessary until a scientist is satisfied with the investigation question.

Read through Table 1.15.6 to see examples of questions formed from the elements of the claims that are refined.

TABLE 1.15.6 Examples of questions formulated from a claim

Example Claim 1: Cold fusion could provide a limitless supply of energy to the world.		
Elements	**Elaboration of the claim**	**Formulated questions**
Heat engines require a heat source and a cold sink	The heat source and the cold sink must be different temperatures	Can the temperature of the heat source and cold sink be brought closer together?
Fusion requires high temperature and pressure to start and sustain	Repulsion forces must be overcome	What is the lowest temperature and pressure required to overcome the repulsion forces?

Example Claim 2: Photons are a better source of fuel than atoms		
Elements	**Elaboration of the claim**	**Formulated questions**
Photons are massless	Thrust requires a change in mass with time	Can a massless particle provide thrust?
Storage – batteries	Molecules of fuel store chemical energy.	Can stored photons provide as much power as chemical fuel?
Efficiency	The intensity of light decreases with the inverse squared law	Does the sun emit enough light to allow interstellar travel?

REFINING THE RESEARCH QUESTION

One of the questions in your journal will become your research question. As you conduct research into the independent and dependent variables, new information will refine the question so it is more specific.

Since the forming and finding criterion assesses the development of the research question from the claim, it is important to record your development of conceptual understanding and the knowledge you gain about the relationships between variables.

Table 1.15.7 compares a formulated question with a developed research question. Always get the teacher to assess your research question.

TABLE 1.15.7 Development of the original questions formulated into research questions

Example Claim 1: Cold fusion could provide a limitless supply of energy to the world.		
Formulated question	**Refined research question**	**Variables**
Can the temperature of the heat source and cold sink be brought closer together?	Can the temperature difference between the cold sink and the heat source in a heat engine be decreased without decreasing efficiency?	*Dependent:* efficiency *Independent:* temperature difference
What is the lowest temperature and pressure required to overcome the repulsion forces?	What is the lowest temperature required to overcome the electromagnetic repulsion in the Deuterium–tritium fusion process?	*Dependent:* electromagnetic repulsion *Independent:* temperature

Example Claim 2: Photons are a better source of fuel than atoms		
Formulated question	**Refined research question**	**Variables**
Can a massless particle provide thrust?	Is the quantity of photons required to provide enough thrust to a spacecraft to enable comparable acceleration to traditional chemical propulsion feasible?	*Dependent:* acceleration *Independent: quantity of photons*
Can stored photons provide as much power as chemical fuel?	Is the energy density of electrochemically stored photovoltaics similar to the energy density of chemical fuel?	*Dependent:* energy density *Independent:* type of fuel
Does the sun emit enough light to allow interstellar travel?	Is the intensity of light emitted by the sun sufficient to accelerate a craft to 0.1c before it leaves the solar system	*Dependent:* acceleration *Independent:* intensity of light

Your research investigation report requires a considered rationale for the research question, displaying its clear development from the claim. Outline this step-by-step development, justifying the steps using scientific concepts, knowledge and understanding.

Your research question must explicitly identify the dependent and independent variables. The research question must be connected to the considered rationale and the topic of study.

PUTTING IT ALL TOGETHER

The structure of the research report is not mandated by the assessment specifications but needs to be presented using appropriate report conventions, such as appropriate headings and language and acknowledge the source of the information using referencing conventions (see module 1.8).

Possible report structures include headings such as:

- Claim, Rationale, Research question, Introduction or Background, Analysis and Interpretation, Conclusion and Evaluation,
- Or organised under the headings of the instrument-specific marking guide (ISMG) criteria as stated in the QCAA syllabus; Forming and Finding, Analysing, Interpreting and Evaluating
- Or you may elect to organise your report in a different but logical order.

The sample research investigation report that follows, covers the ISMG criteria and may be used as a reference tool. Use this as a model for reference.

Forming and finding

Claim: No Air Conditioner Needed: These Buildings Cool Themselves

Rationale

The article linked to the above claim focuses on uses of bioclimatic building design in Pomona, California which uses ventilation and airflow rather than air-conditioning to cool the building and as a result significantly reduces the need for mechanical cooling and reduces its energy consumption (Wetsman, 2018). In 2022, Queensland was responsible for 25% of energy consumption of the whole country (Australian Government, 2022), so significantly reducing its energy consumption would have a large effect on the rest of Australia. As stated in the article "depending on where you are, you'll implement different techniques" (Wetsman, 2018), therefore this report will explore different building design techniques that could potentially be implemented in Queensland (QLD).

However, the claim is a broad statement and some aspects of it must be specified more clearly to accurately investigate it, for example, 'cool themselves'. The average temperature in Pomona, California in the summer is 87°F (Weather Spark, 2024). (roughly 30°C), the article agrees and additionally claims that the building is cooled to a 'very comfortable' 73°F, or approximately 22°C. In QLD the average temperature moderated by air-conditioning is around 25°C (Gall, 2023), therefore this investigation will focus on whether bioclimatic design techniques would reliably cool buildings to or close to 25°C. There are many techniques designed to cool buildings, types of insulation, green roofs, double glazed windows for example. 'Old Queenslander' style homes were "designed for a sub-tropical climate,...[and thus were]...elevated above-ground to allow air to flow underneath for increased ventilation" (Homes to Love, 2022). Though modern architecture has shifted its priorities away from ventilation.

Furthermore, the claim just references 'buildings' though there are many different types of buildings with different features and therefore different ideal ways of using bioclimatic design to cool those buildings. For example, residential homes often have slanted roofs and are relatively shorter compared to office buildings and community buildings such as schools. This investigation will focus on bioclimatic design features most suited towards office buildings, both built in the future and that are already finished. For this reason, ventilation in a similar style to that of an 'Old Queenslander' house would not be feasible for tall and already grounded office buildings. Office buildings typically have flat roofs and windows on all sides and across the length of the wall, meaning they could be suitable for additions of solar control window film and rooftop gardens. Solar control window film is applied to the window glass and is designed to absorb most of the heat that the windows would otherwise let through, which could be crucial for a building with as many windows as an office tends to have (Li, Tan, Chow, & Qiu, 2015). Research into rooftop gardens also shows they can absorb heat and reduce heat transfer through the roof, which again could have a large effect on the overall temperature of the building (Wong, et al., 2002). This report will investigate the potential benefits and effects of solar control window films and rooftop gardens on office buildings.

Research question

Within Queensland, is it viable to reduce the need for air-conditioning, and therefore energy consumption, in existing office buildings with solar control window films and rooftop gardens such that the building's inside temperature remains at or around 25°C (Gall, 2023)?

1.16 Analysing

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- identify the variables in the research question
- determine the evidence required to evaluate the validity of the research question
- identify relevant patterns and trends in the data
- explain the patterns between the two variables
- identify the limitations or gaps exist in evidence.

The Analysing criterion is assessed in relation to just the identification of enough data that enables the research question to be answered and identify the limitations of the sources of the data.

Analysing evidence describes relationships between dependent and independent variables. The data should be presented from more than one source and the overall trend from several authors needs to be identified.

ANALYSING EVIDENCE

A trend or pattern is the general change in one characteristic with respect to another. In science, these are generally represented in the form of a graph with the dependent variable on the *y*-axis and the independent variable on the *x*-axis. Refer also to the graphing information in Module 1.6 of Part A.

The first thing to notice about the trend is the shape of the graph. If there is a relationship between two variables the trends can typically be categorised into one of five categories; linear, power, inverse, exponential and logarithmic.

Figure 1.16.1 shows a comparison of two linear trends. The graph shows the change in the mass of product as a function of time. While a trendline for each is shown no error bars are included for this discussion. When analysing relationships, it can be necessary to compare the effects of changing conditions on the dependent variable. As well as determining the gradients of the curves, key features such the *x*- and *y*-intercepts are important. While both linear graphs show that as time increases the mass of product increases, the rate of increase or gradient is greater for the dashed line. The dashed line passes through the origin, whilst the solid line extrapolates at a negative intercept.

Note, the analysis criterion identifies the relationship but does not assess the reasons for the relationship. That will be assessed in the Interpreting criterion.

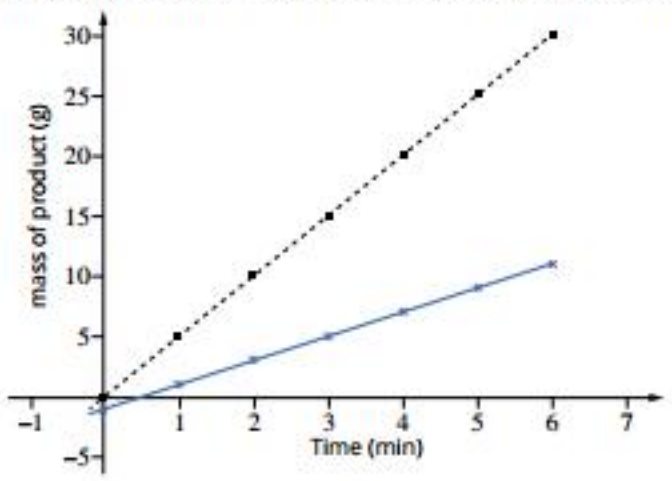

FIGURE 1.16.1 Comparison of the formation of product of a reaction under different conditions

Look at Figure 1.8.3 on page e77. It shows an example of research evidence and how it can be reinterpreted. 1.8.3a shows the original evidence that the student found through research (data is of the light curve of distant star as an exoplanet passes in front of it). 1.8.3b is the student record of their interpretation of the evidence found in the resource.

LIMITATIONS OF THE DATA

All studies are affected by limitations. So, when analysing the data it is important to identify the limitations. Limitations can often be grouped into three categories:

- Elements of the methodology
- Study design that impacts the interpretation of the research results
- Differences between the studies or sources used to investigate the relationship.

Examples of common methodological issues

Selection of samples

This can result in a selection bias if the sampling method results in the selection of samples that do not reflect the general population or population concerned.

Insufficient sample size for statistical measurements

It is critical to have a sufficient sample size to draw valid conclusions. More precise results can be obtained if a larger number of samples are collected, which also enable the results to be generalised to a larger population. In contrast, if the sample size is too small it can be difficult to identify significant relationships in the data.

Lack of previous research studies on the topic

If the research cited is one of a limited number into the issue the lack of available or reliable data can be difficult to make firm conclusions or make connections between studies or the findings and the real world.

Methods/instruments/techniques used to collect the data

While it is unlikely that the students will have experience in using many of the instruments used to collect the data, the limitations in the methodology should be outlined in the discussion section of the research paper. This could include but is not limited to the instruments level of detection.

Differences between the studies or sources used to investigate the relationship

While they may have the same dependent and independent variables, they are unlikely to have used exactly the same methods, materials, or context. Additionally, even if studies elucidate the same relationship between variables, they may show differences in the degree or extent of the relationship. For example, foam batt insulation installed in houses in Canada experience a different range of temperatures than houses in Australia. Findings from studies from different countries would have to be compared with this difference in context in mind.

When reading the research papers, refer to the collection of sufficient and relevant raw data in Part B. This will help evaluate the analysis of the data and identify limitations of the methodology.

As with identification of the trends and patterns, the analysis criterion only assesses the identification of the limitations of the research. The role these limitations played on the data collect and potential impact of the study, including the inability to generalise the research findings will form part of the Evaluating criterion

Furthermore, the report should discuss possible ways to overcome the limitations in future studies, such as alternative methodologies and ways to avoid issues.

Ways to discuss the limitations

When identifying the limitations of the study there are ways to introduce the discussion on the limitations.

- Possible limitations of the study include …
- The first is the…The second limitation concerns the…
- The empirical results reported by … should be considered in the light of some limitations.
- This research is subject to several limitations.
- The primary limitation to the application of these results is…
- The design of the current study is subject to limitations.
- The major limitations in this study that could be addressed in future research are firstly, the study focused on …. Second …
- Having data sources that have used different testing methods or materials can create limitations in the ability to answer the research question. For example, vehicle crash test results from NCAP (Europe) and ANCAP (Australia) use slightly different testing methods which may introduce limitations when it comes to comparison. Note that you will be using data from a number of sources to determine the overall trend, and it is unlikely that these researchers used exactly the same methods or materials.

Sufficient and relevant

Similarly when deciding whether the sources are relevant or sufficient, refer to the start of this module. The analysis criterion uses the terms sufficient and relevant. However, in this case the terms refer to the evidence. Was the data that was analysed 'enough and connected with the investigation' to enable the research question to be fully answered.

PUTTING IT ALL TOGETHER

When writing the research report, it is important to evaluate the report against each criterion in the ISMG to assess the quality of the response. The analysis criterion is focused on the evidence that is collected and identifying and describing patterns or trends that are evident and connected to the research question. Therefore, it is critical that a student identifies aspects of the research question that need to be answered. This will enable the searching for and selection of information related to these aspects.

Once the evidence has been found, the trends need to be identified and used to answer the research question. Remember, that the analysis criterion is only assessed against identification of the patterns and identifying the limitations of the research. So, to get the highest mark, the report needs to collect and analyse enough information to answer the research question.

The sample research investigation report that follows, covers the ISMG criteria and may be used as a reference tool. Use this as a model for reference.

The sample research investigation report shows the analysis of evidence for the research question developed from the claim and covers the ISMG criteria. It may be used as a reference tool. Use this as a model for reference.

Analysing

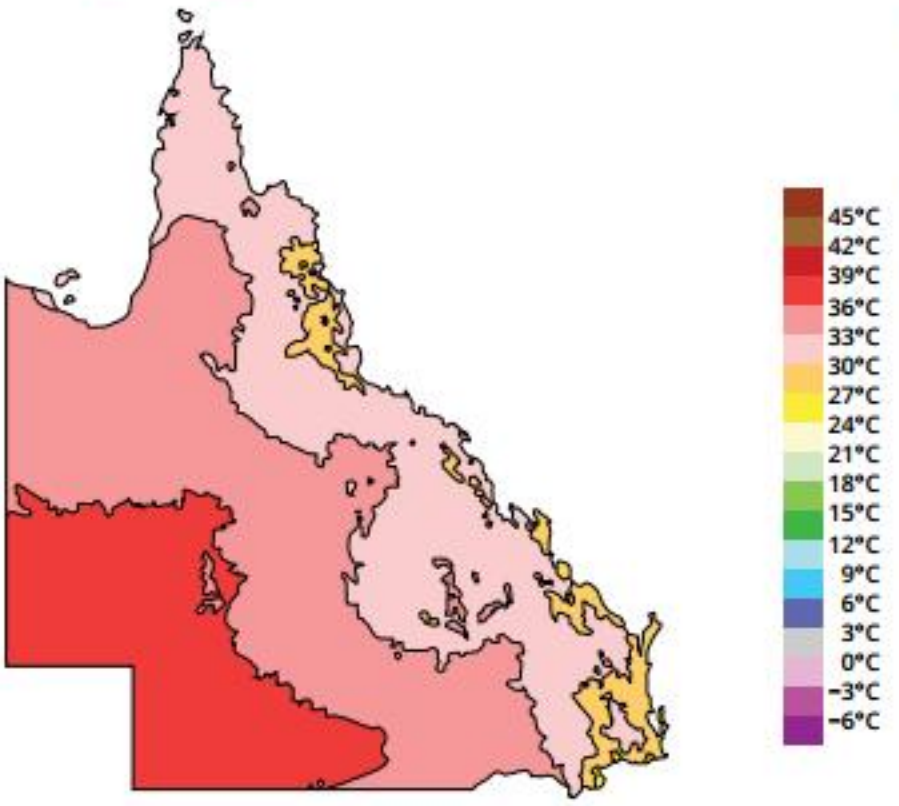

FIGURE 1 Mean daily maximum temperature across Queensland in 2023 (Bureau of Meteorology, 2023)

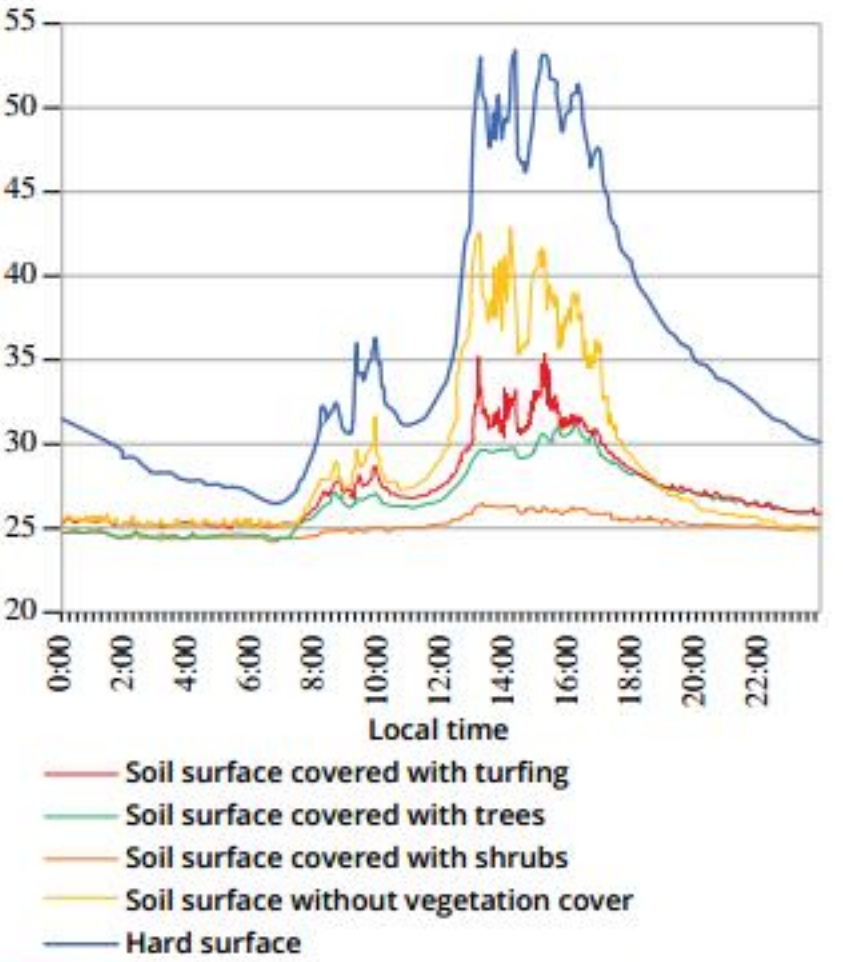

FIGURE 2 Comparison of measured surface area temperatures of multi-story office buildings with different kinds of plants (Wong, et al., (2002))

It can be seen in Figure 1 that the mean daily maximum temperature across QLD is between 27°C and 36°C. Office buildings are mostly located in South-East QLD (SEQ) where the mean daily maximum is between 27°C and 30°C. The mean daily maximum range for SEQ is within the range of exterior temperatures used for Figure 2's experimental data, which shows a green roof made of shrubs can cool a multi-story office building to a relatively stable 25°C throughout the day from an exterior temperature of between 25°C and 30°C (stated in rest of report from (Wong, et al., 2002)). Together they suggest that rooftop gardens would be a successful in cooling office building interiors to 25°C, provided the gardens are shrubbery gardens, in the SEQ climate (which has an average daily maximum of 27–30°C) as they were able to do so in a similar climate successfully. In addition, as green roofs are able to cool down building interiors, it can be assumed that it also limits the need for air-conditioning and reduces the building's overall energy consumption.

However, both figures have limitations that effect the accurateness of the data. Figure 1 does not show how the daily maximum temperature is changing over time and may not be representative of the overall temperatures that occur in the QLD climate, therefore reducing the accuracy of the relationship identified (green roofs may not be effective enough to reduce temperatures). Furthermore, the experiment represented in Figure 2 was undertaken in Singapore only has a similar climate to QLD and not the same one (the average temperature in Singapore is 6.1°C warmer than QLD (Climatemps, 2015)) as a result the green roofs again may not be effective enough to reduce interior temperatures to 25°C.

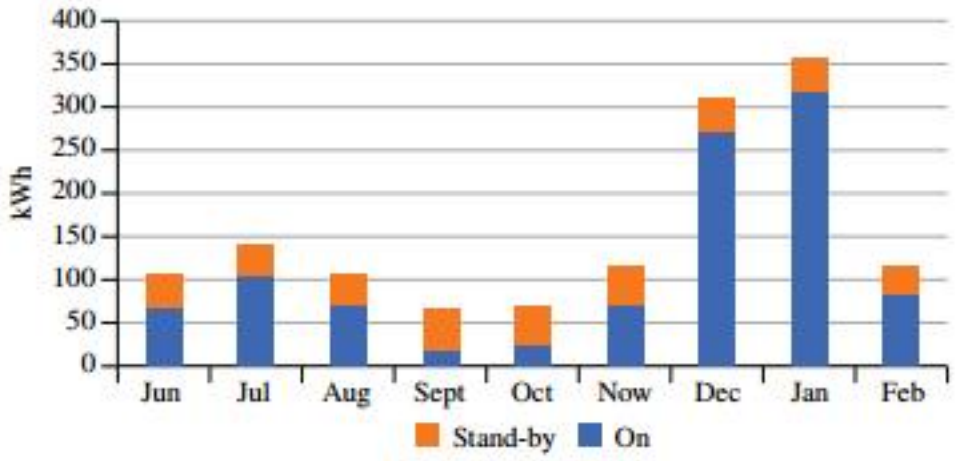

FIGURE 3 Air conditioning run and standby monthly energy consumptions, Brisbane (Law, Osman, Ambrose, James, & White, (2014))

Case no.	Descriptions	Solar film on glazing facing all directions		Solar film only on glazing facing west	
		kWh (%)	kWh/m²	kWh (%)	kWh/m²
1	12 mm clear glazing with SF-1 attached	15,435 (9.5)	44.6	6624 (4.1)	76.7
2	12 mm clear glazing with SF-2 attached	21,253 (13.1)	61.5	7753 (4.8)	89.7
3	12 mm grey tinted glazing with SF-1 attached	3906 (2.7)	11.3	1353 (0.9)	15.7
4	12 mm laminated glazing with SF-3 attached	9272 (5.9)	26.8	2601 (1.7)	34.9
5	6 mm double clear glazing with SF-1 attached	7592 (4.7)	22.0	2911 (1.8)	33.7

FIGURE 4 Electricity saving for an office building with solar window film applied in 5 cases (Li, Tan, Chow, & Qui, (2015))

Figure 3 shows that during the summer months (December, January and February), Brisbane consumes significantly more energy via air-conditioning, 669 kWh running and 184 kWh on standby, than during the winter months (June, July, August), 243 kWh running and 114 kWh on standby, and spring months (September, October, November), 112 kWh running and 137 kWh on standby.

Figure 4 conveys the experimental energy saving capabilities of solar control window film through reducing air-conditioning requirements. The maximum potential energy reduction shown in the experiment is 13.1% and, after applying that reduction to the data from Figure 3, solar control window film has the potential to reduce Brisbane's energy consumption to 581 kWh (–88 kWh) in the summer months. Building interiors would be cooled (though the actual quantitative reduction temperature is uncertain) and as a result reducing the need for air-conditioning. Again, however, both data sets are limited in their accuracy.

The data in Figure 3 relates to air-conditioning of households. This report investigates effects of bioclimatic design on office buildings, which would have a higher energy consumption in comparison, but also most likely contains more windows, so the window film could easily be either more or less effective than predicted. Additionally, the measure of energy consumption reduction in Figure 4 may be specific to one office building and/or one type of air-conditioner and therefore it may not be correct to apply its data to all office buildings. For example, some air-conditioners are more efficient than others so the energy reduction would be greater on most other air-conditioners, or, the building may have had a lower than average number of windows making the film less effective so the energy reduction would also be greater on other buildings that had more windows.

1.17 Interpreting

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- evaluate the research process
- understand the steps and requirements for a justified argument
- identify the steps necessary to develop a justifiable conclusion.

The interpreting criterion is assessed in relation to creating scientific arguments and conclusion and use of scientific language to address the research question.

To achieve the highest mark (5) in the Interpreting criterion you need to create justified scientific arguments and a justified conclusion to answer the research question and present the results in the form of a scientific report using fluent language and representations.

JUSTIFYING AN ARGUMENT

When constructing a scientific argument, the claim, the evidence and the scientific reasoning need to be considered:

- The claim is what is known.
- The evidence is how this is known.
- The scientific reasoning is why does the evidence support or refute the claim.

The QCAA glossary if cognitive verbs defines 'justify' as 'to give reasons or evidence to support an answer, response or conclusion; show or prove how an argument, statement or conclusion is right or reasonable'.

A scientific argument is a statement supported by multiple pieces of evidence that is measured or observed. The argument links the evidence and reasoning together with scientific facts and knowledge. It is important to recognise that the argument could either corroborate the claim or provide evidence that refutes the claim.

Therefore, the investigation needs to use the information and evidence collected from the research to answer the research question rather than simply opinions or beliefs that cannot be empirically verified.

The Introduction outlined terms and concepts related to the topic, which were used to develop the research question. This helped identify variables linked to the research question to be analysed. Then the Analysis section of the report identified patterns and trends in the data related to the research topic.

The Interpreting section of the report needs to explain the trends between the variables to explain the research question.

Common things to avoid

When writing the justification, it is important to be concise and to the point. Select data and explain how the evidence is linked to the research question. Ignore evidence that has no relevance to the research question.

Be selective about the information discussed; the specifications of the assessment task state that the length of the report is limited to 2000 words. The justification needs to emphasise the significance of the research to the research question or topic. How do the trends identified in the analysis section support the conclusion that was drawn? If the data does not directly address the question it should be removed from the report. It is not necessary to use the whole of the data from the research; only use parts of the data that address the research question.

DRAWING A CONCLUSION

When writing the conclusion *make* sure that it explicitly answers the research question. The easiest way to do this is to state the research question and summarise how the evidence supports the research question in about 150 words. In the summary, refer to the key evidence and authors or figures. In addition, concisely outline key limitations and how they contradict the conclusion with respect to the research question. The conclusion usually contains the scientific argument for the dependent and independent variables relationship that has been identified.

The conclusion is sometimes positioned after the analysis and sometimes at the end of the report. Its placement in your report will need to make sense to you and maintain the flow of ideas:

Option 1: Forming and finding → Analysis → conclusion → evaluation

Option 2: Forming and finding → Analysis → evaluation → conclusion

The student sample provided on page e115 of this chapter uses the first of these options, grouped together under the heading 'Conclusion and Evaluation'.

PUTTING IT ALL TOGETHER

There is no single way of creating a justified argument to answer the research question or write the conclusion. The interpretation of the research collected simply needs to create justified *arguments* that use the evidence to explain and answer the research question to form a justified conclusion.

The following conclusion and evaluation is for the sample research investigation report from section 1.16 Analysing. It may be used as a reference tool. Use this as a model for reference.

Interpreting

Conclusion and evaluation

Overall, the evidence found in this investigation supports the research question and agrees it would be viable to reduce the need for air-conditioning in QLD's existing office buildings, by at least 13.1% and in addition reduce energy consumption, by using solar control window films and rooftop gardens to cool the interior of the building from an exterior temperature of between 25°C and 30°C to around 25°C. From figures 1 and 2, it can be inferred that rooftop gardens will be able to cool office building interiors to a comfortable temperature despite the hot summer QLD temperatures (27°C and 30°C). Furthermore, figures 3 and 4 demonstrate how total energy consumption in summer could be significantly reduced from 669 kWh to 581 kWh by reducing the need for air-conditioning.

Quality of evidence

As shown by the Quality of Evidence table (Appendix 1), the evidence used to form this conclusion is highly relevant to the topic, peer-reviewed and/or from a reputable publisher and consistent with other credible sources. However, three of the four pieces of evidence were produced more than 5 years ago, up to 22 years ago, meaning that they possibly do not reflect contemporary technology as accurately as they could, though each of them was published as part of an experiment or report where there was otherwise limited additional, more current research. Figure 2, the oldest produced 22 years ago, was part of an investigation into the effects of rooftop gardens on interior building temperature, therefore in the time since its production there may have been advances in technology that improve the effectiveness of the gardens or evidence that a different type of plant may be more effective than shrubbery. Figure 3 shows energy consumption from air-conditionings from 10 years ago, air-conditionings may have become more energy efficient since then. Finally, figure 4, similar to figure 2, was part of an investigation into the effects of solar control window film, the technology for which may also have improved in the 9 years since its publication to become more effective in energy reduction and interior cooling.

Extrapolation

The findings of this investigation do not refute the original claim, No Air Conditioner Needed: These Buildings Cool Themselves, although not all aspects of the claim were not considered. These aspects include: cooling different types of buildings; applicability to the rest of Australia and other different climates; and other bioclimatic techniques that could be used for the same purpose.

1.18 Evaluating

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- evaluate the research process
- identify the steps necessary to develop a justifiable conclusion
- evaluate the quality of the evidence
- extrapolate the conclusion to the original claim.

The evaluating criterion is assessed in relation to evaluating the quality of the evidence, generalising the information to the original claim and suggesting improvements and extensions that relate to the claim.

To achieve the highest mark (5) in the evaluating criterion you need to evaluate the quality of information used to support the scientific arguments. This requires an explanation of the limitations of the data including an assessment of the statistical quality of the data, such as R value or error bars. In addition, while the focus of the report is to justify a very narrow research question, this section needs to generalise the findings to the much wider claim, i.e. if the findings were more widely applicable how this would impact the claim. Finally, what improvements and extensions would strengthen the findings and further justify the answer to the research question.

EVALUATE THE QUALITY OF EVIDENCE

The analysis section of the report identified limitations in the data. This section of the report needs to explain the how the limitations in the data identified and the sources used to support the argument affected the ability to evaluate and answer the research question.

Questions that could be useful to answer when evaluating the reliability of the data include:

- Were the statistical measures of the data good and appropriate?
- This could be through a R value close to 1 or very small error bars in the data trend.
- Was the sample size sufficient to say that the findings were valid?
- As the sample size increases the standard deviation of the results decreases, meaning that the chance of results being skewed by a single outlier is less.
- Were the findings reproducible?
- The results of the research investigation were corroborated by other studies and research institutions.
- The experiments in the study were repeated with different techniques and the findings were consistent or independent of the methodology chosen, without a justifiable reason why they might vary.
- Did the result occur only under very specific conditions and were these conditions applicable to the real world scenario?
- Was the methodology and instrumentation able to be applied appropriately to the situation studied?
- If the study had to investigate concentrations significantly greater than those that exist in the real-world can the findings of the research be applied to the real world?
- Are the theories that the authors used to support their findings still valid?

It is important not to just repeat the statements earlier in the analysis but to describe the effect on the investigation.

In addition to evaluating the data analysed the investigation needs to evaluate whether the sources that were used were reliable.

EVALUATING SOURCES FOR VALIDITY AND RELIABILITY

Determining the validity and reliability of a source can be a challenging task. For some sources, it is easy to find details about the author and quality of the evidence, while others only contain content and do not offer any other details. Another difficulty is when learning about a new topic or concept, we are all novice learners so it can be challenging to tell if a source is valid or not.

Examples of questions to consider when evaluating the sources include:

- Who or what organisation commissioned the report?
- What qualifications do the authors have?
- Is the source peer-reviewed or have a bias that might influence their findings?
- Is the information provided referenced and are the sources of this information reliable?
- When was the research reported? This is important as theories and concepts can be influenced by the year in which they were published.
- Are the findings reported in the publication supported by other sources? This will be found in the introduction, where the author identifies background information and gaps in the current understanding of the topic.

Table 1.18.1 outlines an example of evaluating a resource step-by-step, for the research article (Figure 1.18.1) that is connected to a claim about the effect of silica aerogel particle size on its performance in composite materials for thermal insulation and sound proofing. Connected to a claim comparing herbal shampoo with commercial shampoos.

Effect of silica aerogel on thermal insulation and acoustic absorption of geopolymer foam composites: The role of aerogel particle size

Y.X. Chen [a,b,1], K.M. Klima [b,1], H.J.H. Brouwers [b], Qingliang Yu [a,b,*]

[a] School of Civil Engineering, Wuhan University, Wuhan, 430072, PR China
[b] Department of the Built Environment, Eindhoven University of Technology, P.O. Box 513, 5600 MB, Eindhoven, the Netherlands

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ABSTRACT

Silica aerogel features super thermal insulating and excellent sound absorption. Although the application of silica aerogel in building materials for energy saving has been investigated recently, the role of aerogel particle size on geopolymer foam render can be crucial but is rarely studied. In this research, four kinds of silica aerogel with different particle sizes (2–40 μm, 100–700 μm, 100–1200 μm, 700–4000 μm) are applied in geopolymer foam aerogel render (GFAR) to improve the thermal insulation and acoustic absorption performance. Results show that larger silica aerogel particles are more beneficial for acoustic absorption and thermal insulation while smaller aerogel particles are less effective for insulation properties. The microstructure of GFAR is investigated in-depth with micro-CT, optical microscopy and ultrasonic pulse velocity test. The mechanism of the improved performance of GFAR with different silica aerogel is explained. The optimal geopolymer foam aerogel render (GFAR) reaches a thermal conductivity of 0.133 W/(m·K), an average value of acoustic absorption coefficient of 0.51 with a density of 715.2 kg/m^3. The result of this study is essential to enlighten the use of larger silica aerogel particles in geopolymer foam render, focusing on a low dosage of silica aerogel while utilize its full benefit.

1. Introduction

The energy-saving of the building sector and the comfort of the indoor living environment have received rising attention due to the increasing awareness of sustainability and the quality of life [1]. The building industry is responsible for almost 40% of the total energy and CO_2 emission in developed countries [2]. For now, many countries have already initiated policies to decrease heat loss through building shells [3]. Moreover, the functionalization of insulation materials is also very important, for instance, improving the acoustic absorption performance to increase the quietness of the indoor environment [4,5] and reduce the noise pollution generated from daily life [6]. Therefore, developing newly high-performance insulating lightweight materials is of significant urgency.

Silica aerogel is a super-insulating inorganic material [7], consisting of a 3D network of crosslinking silica nanoparticles and 95%–99% of air [8]. Thanks to the high porosity and low solid thermal conductivity (λ), the effective thermal conductivity of silica aerogel is pretty low, normally achieving 0.012–0.018 W/(m·K) [9]. However, the silica aerogel is very brittle and easy to break, the commercial silica aerogels are always produced in a powder or particle form [10]. It is often incorporated in other matrices, like fibreglass mats or other lightweight materials to facilitate its benefits [11]. Several investigations related to the incorporation of silica aerogel in building materials have already been carried out as presented in Table 1. Ng et al. [12] prepared high-performance aerogel concrete, with bulk density and thermal conductivity of 1300 kg/m^3 and 0.4–0.5 W/(m·K), respectively. The concrete has a low water to binder ratio of 0.20–0.25 and a silica aerogel replacement ratio of 50%–70% with sand. Tao et al. [13] developed normal cement mortar with an aerogel replacement ratio of 60%, featuring a compressive strength of 8.3 MPa and thermal conductivity of 0.26 W/(m·K). Júlio et al. [14] prepared lightweight aerogel aggregate concrete with a 100% replacement ratio of silica aerogel with sand, resulting in concrete with very low thermal conductivity of 0.085 W/(m·K) but compressive strength of only 0.41 MPa. Seo et al. [15] investigated the silica aerogel used in fly ash/slag geopolymer concrete, with an aerogel concentration of 25%–75%. However, the thermal conductivity is relatively high, reaching 0.8 W/(m·K). Zhu et al. [16] investigated the cement-based mortars and coatings with the addition of silica aerogel. The thermal conductivity is low (0.17 W/(m·K)) with a

* Corresponding author. School of Civil Engineering, Wuhan University, Wuhan, 430072, PR China.
E-mail address: q.yu@bwk.tue.nl (Q. Yu).
[1] Authors contribute equally to this work.

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1359-8368/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

FIGURE 1.18.1 A peer-reviewed research article entitled 'Effect of silica aerogel on thermal insulation and acoustic absorption of geopolymer foam composites: The role of aerogel particle size'

TABLE 1.18.1 Evaluation of a resource

Source evaluated: Effect of silica aerogel on thermal insulation and acoustic absorption of geopolymer foam composites: The role of aerogel particle size'

Criteria		Decision	Support/justification
Primary or secondary	Is this an eyewitness account or a second-hand source?	primary	• Research article published in www.Sciencedirect.com • Research results published in article
Validity	Does it contain information that is specifically related to the claim?	yes	• Outlines information directly related to the performance aerogel as thermal insulation
	Is the evidence and information pertinent to the variables in the research question?	yes	• Information, experiment and results are specific to the performance and physiochemical properties of aerogel.
Reliability	Is it current/recent information?	yes	• Published Aug 2022 • This is quite recent, but aerogels are modern materials undergoing a considerable amount of research. There may be newer information available.
	Is it up-to-date in its understanding of relationships?	yes	• Information outlined about thermal conductivity and properties of aerogel
	Is the evidence equivalent to other sources?	mostly	• Table 1 within the article contains a list of six similar experiments.
	Check the credibility—consider who the author is, their qualifications and expertise.	good	authors are from the School of Civil Engineering at Wuhan University or the Department of the Built Environment at Eindhoven University journal of Basic and Applied sciences is a reputable peer-reviewed journal
	Try to find the sample size.	known	Six samples, three trials per sample.
	Try to establish what variables were controlled or measured.	known	methodology of the preparation, storage, and testing of the samples is detailed, including controled variables such as air temperature and humidity.

A judgement could be made about the credibility of this source, such as:

The information and evidence was published by experts in a peer-reviewed journal article that is up-to-date and with variables of experimentation known and directly related to the claim and research question. Though as the results are new, it is yet to be seen if they are substantiated, therefore affecting the reliability of the evidence. This resource is both valid and reliable.

EXTRAPOLATION TO THE CLAIM

The first stage of this assessment involved narrowing the claim to a very specific research question. This could have meant selecting a specific material or smaller temperature or concentration range. The Extrapolating criterion requires inferring how the trends and patterns identified and explained in the earlier sections of the research report could be extended to original claim.

When exploring the claim, the students identified the dependent and independent variables associated with the claim. Thus, questions that can help students extrapolate the findings and conclusion to the claim include:

- what are the dependent, independent and controlled variables associated with the claim?
- what is the impact on the dependent variable when the independent or controlled variables from the research question are extended to include the claim?

Improvements and extensions

Suggest improvements and extension(s) that would complement the research findings and have the potential to provide new evidence that could be used to evaluate the research question (improvements) and claim (extensions) further. These should be linked to the identified limitations (analysis and quality of evidence can just identify the issue). Make sure not to repeat yourself.

The highest performance level requires that suggested improvements need to be considered and relevant. There are two obvious areas that could be the focus of the suggested improvements. Firstly, a good place to start when proposing possible improvements is the limitations in the research and evidence that were identified and explored in the previous sections in the report. Secondly, what information is required to provide more definitive proof of the research question.

As discussed in the limitation, these could come from the methodology or the interpretation of the results. It could be useful to consider the following:

- changes to the method of selecting samples to reduce bias
- increasing the sample size to increase the accuracy of the results or reduce the errors associated with the measurements
- methods/instruments/techniques used to collect the data. If the measurements were below the limit of detection or so low that the associated error was large. Has technology advanced since the previous research that mean that the relationship can be more accurately determined.
- through your investigation what gaps in the evidence did you identify.

These considerations could form the basis for your suggested improvements. While a detailed explanation of these is not required, the report should identify how they would benefit your investigation.

Suggestions of possible extensions to the research investigation could be identified from the information collected as part of the research investigation. Students should ask themselves if there were limits to the scope of evidence available.

- Did the research you found identify areas that could be explored further?
- Could the conclusions from your report be extended to another situation?
- When extrapolating the research question to the claim, were the aspects that could not be proven because the information was not available?

PUTTING IT ALL TOGETHER

There is no singular way of creating a justified argument to answer the research question or write the conclusion. The interpretation of the research collected simply needs to create justified arguments that use the evidence to explain and answer the research question to form a justified conclusion.

The sample research investigation report that follows, covers the ISMG criteria and may be used as a reference tool. Use this as a model for reference for justified arguments that link the research question and evidence, enabling a conclusion supported by reasoning and scientific understanding to be drawn.

The sample research investigation report that follows, covers the ISMG criteria and may be used as a reference tool. Use this as a model for reference.

Conclusion & Evaluation

Improvements and extensions

To fully investigate all aspects of the claim, there are several improvements and extensions that could be made. This report focused on office buildings, however its conclusion could be improved by considering its applicability to other types of buildings, such as residential homes, apartment buildings, community buildings and commercial buildings, and how green roofs and solar control window film could benefit them as well as the effects on a specific building in QLD to gauge specific and quantitative cooling effects from the window film and garden. It could also be improved by investigating the distinct combined effects of both green roofs and the window film to see exactly how much of an effect they would have together instead of just 'an effect'. Additionally, this research could be extended by investigating other bioclimatic techniques for reducing temperature, such as insulation, ventilation and shade etc, which could perhaps be better suited for other types of buildings or climates than the techniques investigated here. Moreover, this report could be extended to include the rest of Australia, and the vast climates that exist in it, and examine whether or not it would be viable for the whole country, as bioclimatic techniques have the potential to reduce air-conditioning usage and energy consumption everywhere, with proper investigation into each area's climate so the most suitable and effective design techniques are identified.

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Appendix

APPENDIX 1 Quality of evidence

Quality of evidence used to form conclusion					
Weighting %	**Aspect**	**Heirarchy**	**Judged**	**Value**	
20	Relevance of Source to RQ	Highly relevant to the topic	Y	20.0	/20
		Moderately relevant			/10
		Not relevant at all			/0
30	Credibility of the Source	Peer-reviewed or from a reputable publisher	Y	30.0	/30
		Authored by an expert in the field			/15
		Lack of clear authorship or affiliation			/0
20	Currency of the Information	Recently published/updated (last 2 years)			/20
		Somewhat recent (last 5 years)			/10
		Outdated or not specified	Y	0.0	/0
30	Consistency with Existing Literature	Consistent with other credible sources	Y	30.0	/30
		Somewhat consistent			/15
		Contradictory with existing literature			/0
Judgement of Quality of Evidence			Excellent (80%)		

All of the evidence is of excellent quality aside from its currency. One source is dated from 2023, extremely current, whereas the others are from 9, 10 and 22 years ago and, for example, the house cooling technology may have improved in the time since then. The current one (2023) is a regularly produced source from a government website, however, the rest are from reports and experiments where there is otherwise limited research, additionally limiting its accuracy and its quality of evidence.

UNIT 1 Thermal, nuclear and electrical physics

TOPIC 1 Heating processes

TOPIC 2 Ionising radiation and nuclear reactions

TOPIC 3 Electrical circuits

Unit 1 objectives

Students will:

- describe ideas and findings about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits
- analyse data about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- evaluate processes, claims and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- investigate phenomena associated with heating processes, ionising radiation and nuclear reactions, and electrical circuits.

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CHAPTER

02 Heating processes

Thermal energy is part of our everyday experience. Humans can thrive in Earth's climatic extremes, from the outback deserts to ski slopes in winter. Due to increasing levels of carbon dioxide in the atmosphere, the Earth is getting warmer. In 2023, the Earth was the warmest since records began in 1890. These higher temperatures increase the severity of bushfires and increase the rate of evaporation from pastures, which dries the land and reduces the level of food production.

Temperature is a measure of the motion of particles. Different substances will absorb different amounts of heat to raise their temperature or to change state from solid to liquid to gas, depending on their atomic structure. Heat energy can be transmitted through materials in different ways, depending on the material's properties. Energy is conserved in the universe, but in each energy transfer, energy can be 'wasted' as less useful forms, decreasing the efficiency of the energy transfer.

Syllabus subject matter

Topic 1 • Heating processes

KINETIC PARTICLE MODEL AND SPECIFIC HEAT CAPACITY

- Describe the kinetic particle model of matter. **2.1**
- Describe the concepts of thermal energy, temperature, kinetic energy, heat and internal energy. **2.1**
- Explain heat transfers in terms of conduction, convection and radiation. **2.3**
- Use $T_K = T_C + 273$ to convert temperature measurements. **2.2**
- Explain that a change in temperature is due to the addition or removal of energy from a system (without phase change). **2.2**
- Describe the concept of specific heat capacity. **2.4**
- Solve problems involving specific heat capacity using $Q = mc\Delta T$. **2.4**
- Interpret data from specific heat capacity experiments. **2.4**

PHASE CHANGES AND ENERGY CONSERVATION

- Explain, in terms of the internal energy of a system and the kinetic particle model of matter, why the temperature of a system remains the same during the process of state change. **2.5**
- Describe the concept of specific latent heat. **2.5**
- Solve problems involving specific latent heat using $Q = mL$. **2.5**
- Describe the concept of thermal equilibrium in terms of the temperature and average kinetic energy of the particles in each of the systems. **2.6**
- Explain the process in which thermal energy is transferred between two systems until thermal equilibrium is achieved, and recognise the relevance of this to the laws of thermodynamics. **2.6**

- Solve problems involving specific heat capacity, specific latent heat and thermal equilibrium. **2.6**
- Explain how a system with thermal energy has the capacity to do mechanical work. **2.7**
- Explain that the change in the internal energy of a system is equal to the energy added or removed by heating plus the work done on or by the system and recognise this as the first law of thermodynamics and as a consequence of the law of conservation of energy. **2.7**
- Explain how energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so that the amount of useable energy is reduced. **2.7**
- Describe the concept of efficiency. **2.7**
- Solve problems involving the efficiency of heat transfers using $\Delta U = Q + W$ and $\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$ **2.7**

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2.1 The kinetic particle model

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the kinetic particle model of matter
- apply the kinetic particle model to solids, liquids and gases
- understand potential and kinetic energy
- understand heat, temperature and thermal energy
- recognise the internal energy of a substance is a combination of its potential and kinetic energy.

In the 16th century, Sir Francis Bacon, an English essayist and philosopher, proposed a radical idea: that heat is motion. He went on to write that heat is the rapid vibration of tiny particles within every substance. At the time, his ideas were dismissed because the nature of particles was not fully understood. An opposing theory at the time was that heat was related to the movement of a fluid called 'caloric' that filled the spaces within a substance.

Today, it is understood that all matter is made up of small particles (atoms or molecules). Using this knowledge, it is possible to look more closely at what happens during heating processes. This section starts by looking at the kinetic particle model, which describes the behaviour of the particles in a substance.

KINETIC PARTICLE MODEL OF MATTER

A **model** is a representation that describes or explains the workings within an object, system or idea. Models can be used to simplify complex structures or systems. Scientists use models to understand and analyse complex systems, and to make predictions about these systems.

The behaviour of particles in a substance is complex, so a model is used to describe it.

Some philosophers in the 17th century believed that heat was a fluid that filled the spaces between the particles of a substance and flowed from one substance to another. This is known as the 'caloric' theory. When caloric flowed from one substance into another, the first object cooled down and the second object heated up. Many attempts were made to detect caloric, but none were successful. It was assumed that caloric had no mass, odour, taste or colour. Scientists now know that caloric simply does not exist.

Much of our understanding of the behaviour of matter today depends on a model called the **kinetic particle model** (also known as kinetic theory).

The kinetic particle model of matter states that the small particles—atoms or molecules—that make up all matter have kinetic energy. This means that all particles are in constant motion, even in extremely cold solids. It was thought centuries ago that if a material was continually made cooler, there would be a point at which the particles would eventually stop moving. This coldest possible **temperature** is called **absolute zero** and will be discussed later in Module 2.2.

These are the assumptions of the kinetic particle model:

- All matter is made up of many very small particles (atoms or molecules).
- The particles are in constant motion.
- No kinetic energy is lost or gained overall during collisions between particles.
- There are forces of attraction and repulsion between the particles in a material.
- The distances between particles in a gas are large compared with the size of the particles.

The kinetic theory applies to all states (or phases) of matter: solids, liquids, gases and plasmas.

Solids

In a solid, the matter holds its fixed shape because the particles exert forces on each other. There are also repulsive forces without which the attractive forces would cause the solid to collapse. In a solid, the attractive and repulsive forces hold these particles in more or less fixed positions, usually in a regular arrangement or lattice, as shown in Figure 2.1.1a. The particles in a solid are not completely still; they vibrate around average positions. The forces on individual particles are sometimes predominantly attractive and sometimes repulsive, depending on their exact position relative to neighbouring particles.

Liquids

In a liquid, the particles exert a balance of forces of attraction and repulsion. Compared with a solid, the particles in a liquid have more freedom to move around each other and will therefore take the shape of the container. Particles collide but remain attracted to each other, so the liquid remains within a fixed volume but with no fixed shape (Figure 2.1.1b). In general, a liquid takes up a slightly greater volume than the same amount of matter would in the solid state. One exception is water, which is less dense as a solid (ice).

Gases

In a gas, particles are in constant, random motion, colliding with each other and the walls of the container. The particles move rapidly in every direction, quickly filling the volume of any container and occasionally colliding with each other (Figure 2.1.1c). A gas has no fixed volume. The particle speeds are high enough that, when the particles collide, the attractive forces are not strong enough to keep the particles close together. The repulsive forces cause the particles to separate and move off in other directions.

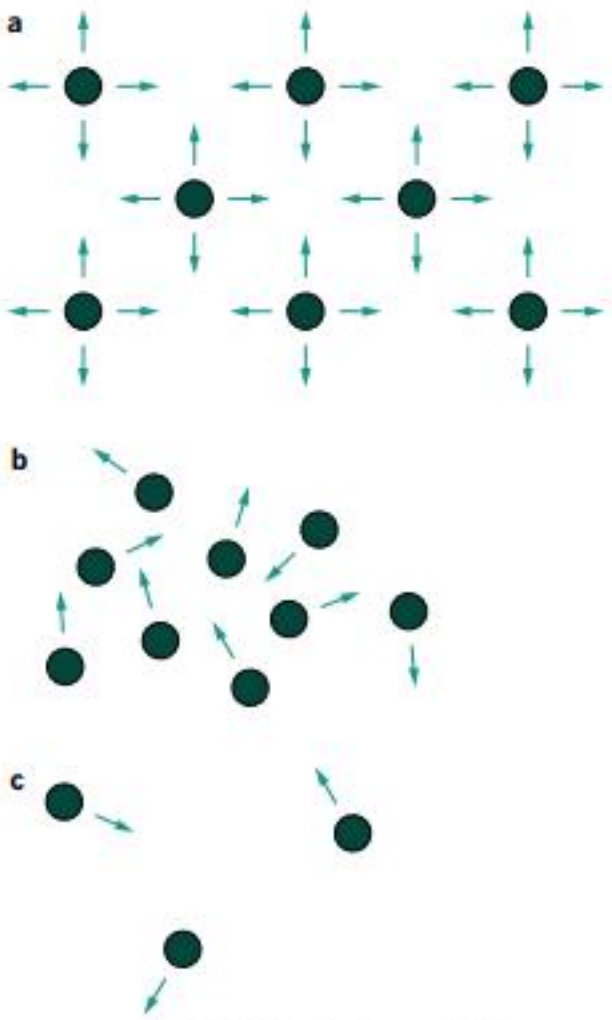


FIGURE 2.1.1 (a) Molecules in a solid have low kinetic energy and vibrate around average positions within a regular arrangement. (b) The molecules in a liquid have more kinetic energy than those in a solid. They move more freely and will take the shape of the container. (c) Gas molecules are free to move in any direction.

Plasmas

Plasma exists when matter is heated to very high temperatures and electrons are freed (ionisation). A gas that is ionised and has an equal number of positive and negative charges is called plasma. The interior of stars consists of plasma. In fact, most of the matter in the universe is plasma (Figure 2.1.2).

FIGURE 2.1.2 99.9% of the visible universe is made up of plasma.

ENERGY

Energy is a very important concept in the study of the physical world and is a focus in all areas of scientific study. Later chapters investigate energy in more detail.

Work is defined as being done when a force is applied to an object and moves it.

Energy is a measure of an object's ability to do work. Work is done when energy is transferred or transformed. For example, raising an object's temperature or moving or lifting an object is referred to as doing work. Work is measured in joules. The symbol for joules is J. Figure 2.1.3 shows the amount of energy available from some energy sources.

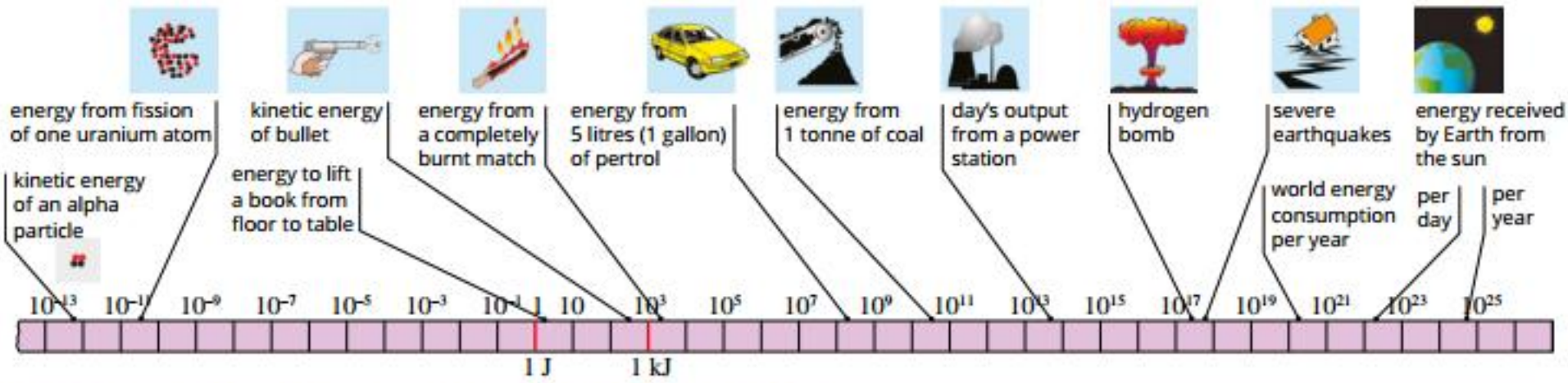

energy from fission of one uranium atom
kinetic energy of bullet
energy from a completely burnt match
energy from 5 litres (1 gallon) of pertrol
energy from 1 tonne of coal
day's output from a power station
hydrogen bomb
severe earthquakes
energy received by Earth from the sun
kinetic energy of an alpha particle
energy to lift a book from floor to table
world energy consumption per year
per day
per year
10^{-13} 10^{-11} 10^{-9} 10^{-7} 10^{-5} 10^{-3} 10^{-1} 1 10 10^{3} 10^{5} 10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19} 10^{21} 10^{23} 10^{25}
1 J
1 kJ

FIGURE 2.1.3 The comparative amounts of energy available from several sources

Potential energy

Potential energy is stored energy. Examples of potential energy include gravitational, nuclear, spring and chemical energy. Chemical potential energy is associated with the bonds between the particles of a substance. An increase in the potential energy of particles in a substance results in movement of the particles from their equilibrium positions.

Kinetic energy

Kinetic energy is the energy of movement. It is equal to the amount of work needed to bring an object from rest to its present speed or to return it to rest.

Internal energy and heat

The kinetic particle model can be used to explain the idea of heat as a transfer of energy. **Heat** (measured in joules) is the transfer of **thermal energy** from a hotter to a colder body. Thermal energy is the energy a substance has because of its temperature. Heating is observed by the change in temperature, the change of state or the expansion of a substance. When a substance is 'heated', the particles within the material gain kinetic energy and/or potential energy. Conversely, when the average kinetic energy of the particles in a substance increases, the temperature of the substance also increases.

The term 'heat' refers to energy that is being transferred (moved), so it is incorrect to talk about heat contained in a substance. The term **internal energy** refers to the total kinetic and potential energy of the particles within a substance. Heating—the transfer of thermal energy—changes the internal energy of a substance by affecting the kinetic energy and/or potential energy of the particles within the substance. Individual particles in a substance move back and forth in an ordered manner due to their kinetic energy, and this behaviour can be modelled. In contrast, the internal energy of a system is associated with the chaotic motion of the particles and relates to the behaviour of many particles that all have their own kinetic and potential energy.

- Heating is a process that always transfers thermal energy from a hotter substance to a colder substance.
- Heat is measured in joules (J).
- Temperature is related to the average kinetic energy of the particles in the substance. The faster the particles move, the higher the temperature of the substance.

According to the kinetic particle model, an increase in the total internal energy of the particles in a substance will result in an increase in temperature if there is a net gain in kinetic energy. Hot air balloons are an example of this process in action. The air in a hot air balloon is heated by a gas burner to a maximum of 120°C. The nitrogen and oxygen molecules in the air in the balloon gain energy and so move faster. The air in the balloon becomes less dense than the surrounding air, causing the balloon to float, as shown in Figure 2.1.4.

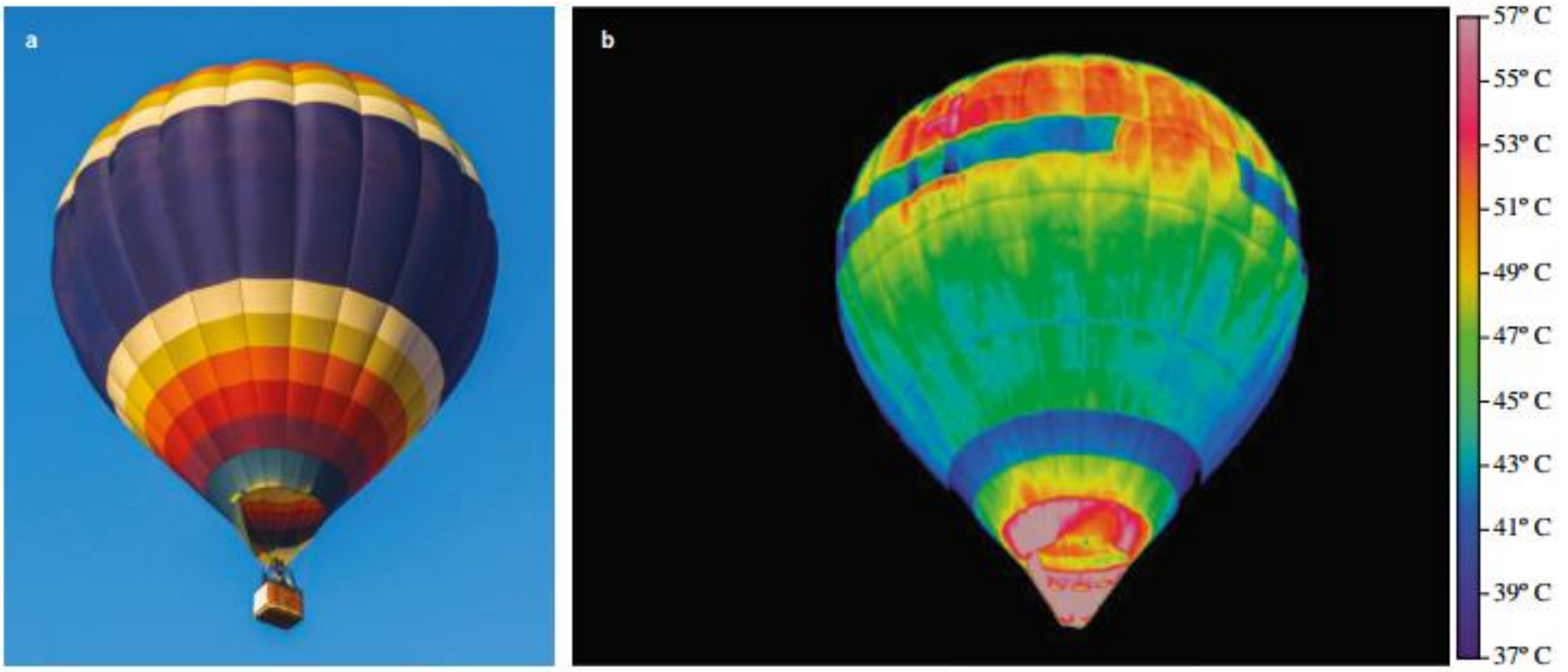


FIGURE 2.1.4 (a) Nitrogen and oxygen molecules gain energy when the air is heated, lowering the density of the air and causing the hot air balloon to rise off the ground. (b) A thermal image shows the temperature of the air inside the balloon.

Sometimes heating results only in the change of state or expansion of an object (phase change), and not a change in temperature. In these cases, the total internal energy of the particles has increased, but only the potential energy has increased; kinetic energy has not changed.

For example, particles in a solid being heated will continue to be mostly held in place due to the relatively strong interparticle forces. For the substance to change state from solid to liquid, it must receive enough energy to separate the particles from each other and disrupt the regular arrangement of the solid. During this 'phase change' process, the energy is used to overcome the strong interparticle forces but does not change the overall speed of the particles. In this situation, the temperature does not change. This will be discussed in more detail in Module 2.5.

Kinetic energy and temperature

As the temperature of a substance increases, the kinetic energy and therefore the speed of the particles also increases. At a particular temperature, the particles in a substance will have a range of kinetic energies. Although most of the particles have similar energies, there are always some particles with a high energy or a low energy. This range of energies is shown on a graph called a **Maxwell–Boltzmann distribution**. Figure 2.1.5 shows how the range of energies is represented in a Maxwell–Boltzmann distribution.

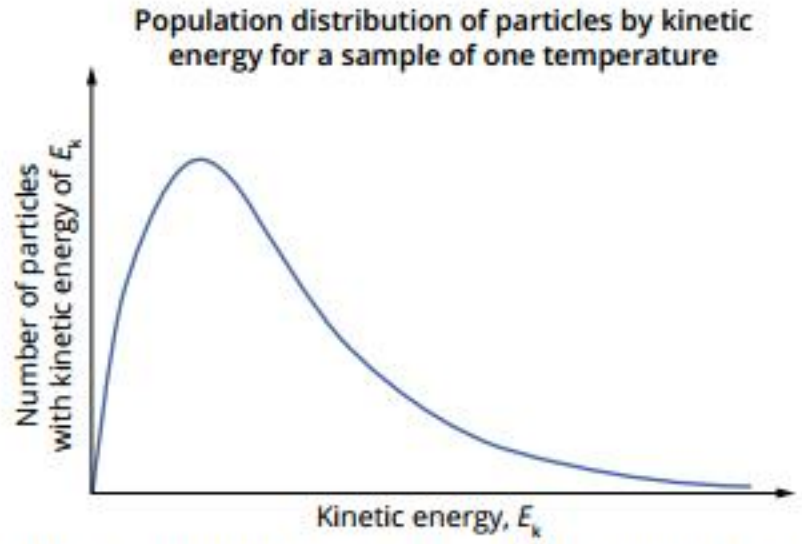

Population distribution of particles by kinetic energy for a sample of one temperature
Number of particles with kinetic energy of E_k
Kinetic energy, E_k

FIGURE 2.1.5 The Maxwell–Boltzmann distribution shows the range of kinetic energies of particles in a sample at a particular temperature. The peak of the graph corresponds to the energy of the greatest number of particles.

As the temperature of a system increases, the average kinetic energy of the particles increases and therefore the average velocity of the particles also increases. Figure 2.1.6 shows the distribution of kinetic energies for a gas at three different temperatures. Notice that the area under the curve, which is equal to the total number of particles in the sample, stays constant when the temperature is changed. As the temperature increases, the increasing average kinetic energy of the particles can be seen by the movement to the right of the peak in the Maxwell–Boltzmann distribution.

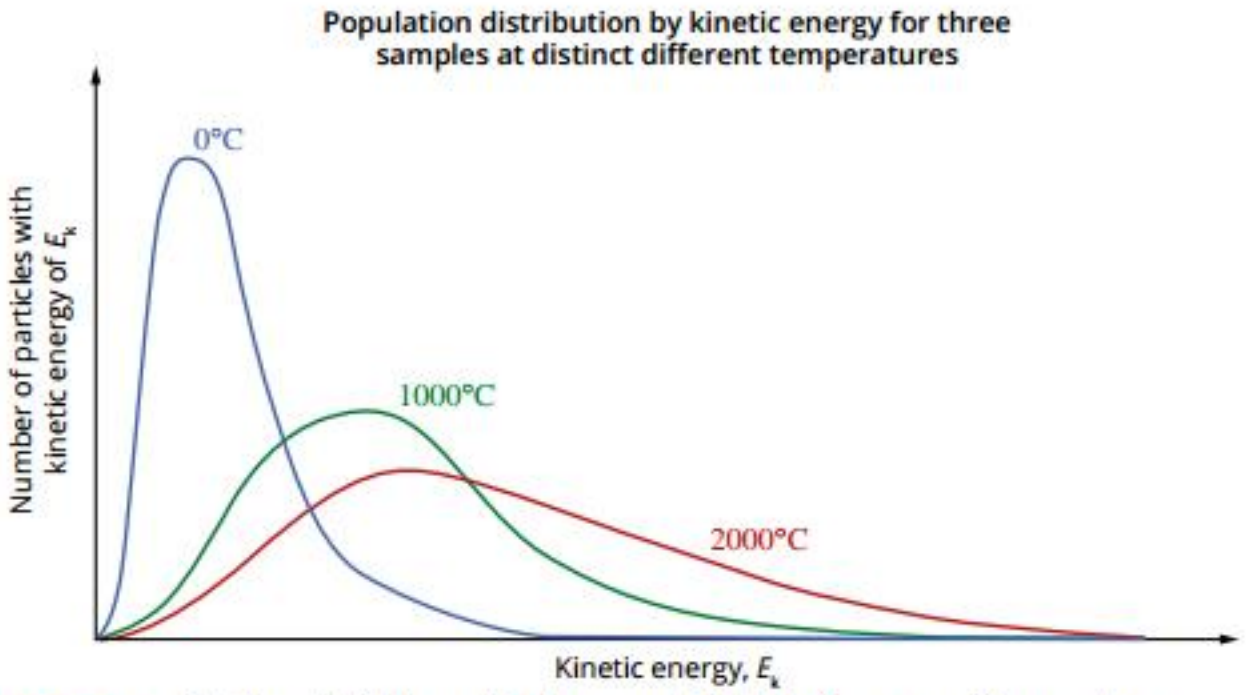

Population distribution by kinetic energy for three samples at distinct different temperatures
Number of particles with kinetic energy of E_k
0°C
1000°C
2000°C
Kinetic energy, E_k

FIGURE 2.1.6 The Maxwell–Boltzmann kinetic energy distribution for a range of temperatures

2.1 Review

SUMMARY

- The kinetic particle theory proposes that all matter is made of atoms or molecules (particles) that are in constant motion.
- In solids, attractive and repulsive forces hold the particles in more-or-less fixed positions, usually in a regular arrangement or lattice. These particles are not completely still; they vibrate about average positions.
- In liquids, there is still a balance of attractive and repulsive forces between particles, but the particles have more freedom to move around. Liquids maintain a fixed volume.
- In gases, the particle speeds are high enough that, when particles collide, the attractive forces are not strong enough to keep them close together. The repulsive forces cause the particles to move off in other directions.
- Internal energy refers to the total kinetic and potential energy of the particles within a substance.
- Temperature is related to the average kinetic energy of the particles in a substance.
- Heating is a process that always transfers thermal energy from a hotter substance to a colder substance.

KEY QUESTIONS

Describe

1 What are the assumptions of the kinetic particle model?

2 Describe the two forms of internal energy.

3 What does the Maxwell–Boltzmann distribution show?

Apply

4 Describe how you measure the change of the average kinetic energy of the molecules within a substance.

5 Describe which way the heat will flow when you put some hot coffee into a cold mug.

6 Explain how a hot air balloon can rise.

7 Use the kinetic particle model to explain why it is hard to compress a solid.

8 Explain how liquids can change shape using the kinetic particle model.

9 Why is it incorrect to talk about how much heat an object has?

Analyse

10 Use the kinetic theory of matter to differentiate between water ice, liquid water and water vapour.

2.2 Temperature

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the difference between absolute and arbitrary scales
- convert temperature measurements between Celsius and kelvin
- explain how a change in temperature is due to an addition or removal of energy from a system.

MEASURING TEMPERATURE

Before thermometers were invented, temperatures were described using vague terms such as 'hot', 'cold' and 'lukewarm'. In about 1593, Italian inventor Galileo Galilei made one of the first thermometers. His 'thermoscope' was not particularly accurate as it did not consider changes in air pressure, but it did suggest some basic principles for determining a suitable scale of measurement. His work suggested that there be two fixed points: the hottest day of summer and the coldest day of winter. A scale like this is referred to as an arbitrary scale, because the fixed points are randomly chosen.

How to measure temperature

To measure temperature, you use properties of materials that change with temperature. Many thermometers, including mercury and alcohol thermometers (Figure 2.2.1), use thermal expansion. Thermal expansion is the expansion of a substance as it increases in temperature. The mercury (or alcohol) expands as it gets warmer, filling more of the thermometer, producing a higher temperature reading.

TEMPERATURE SCALES

Two of the better-known, arbitrary temperature scales are Fahrenheit and Celsius. German physicist Gabriel Fahrenheit invented the first mercury thermometer in 1714. The Fahrenheit scale is often used in the USA to measure temperature, but the Celsius scale is used in most other countries of the world.

Absolute scales are different from arbitrary scales. For a scale to be regarded as 'absolute', it should have no negative values. The fixed points must be reproducible and have zero as the lowest value.

Kelvin temperature scale

When developing the absolute temperature scale, the triple point of water provides one reliable fixed point. The triple point is the point at which the combination of temperature and air pressure allows all three states of water to coexist. The triple point of water is only slightly above the standard freezing point (0.01°C) and provides a unique and repeatable temperature with which to adjust the Celsius scale.

The absolute or **kelvin** temperature scale is based on absolute zero and the triple point of water. Figure 2.2.2 on page 12 shows a comparison of the kelvin and Celsius scales.

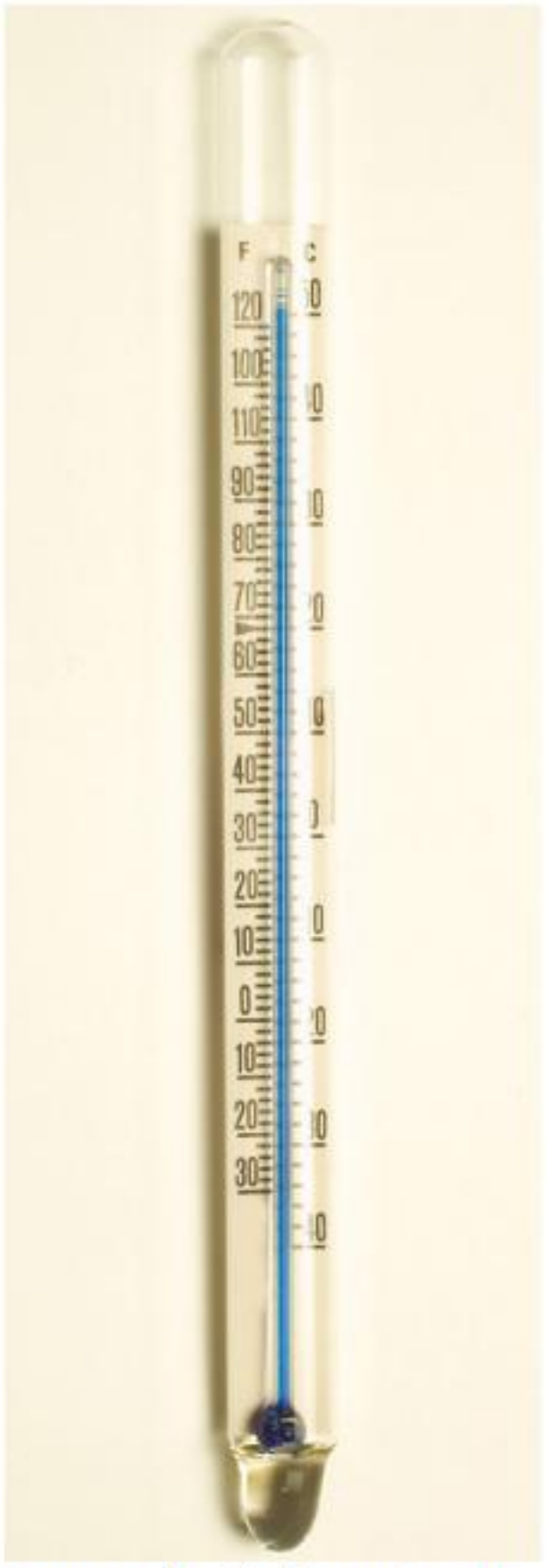


FIGURE 2.2.1 An alcohol thermometer contains alcohol (red or blue, as shown here) instead of mercury (silver).

- The freezing point of water (0°C) is equivalent to 273.15 K (kelvin). This is approximately 273 K.
- The size of each unit (1°C or 1 K) is the same.
- The word 'degree' and the degree symbol are not used with the kelvin scale.
- 0°C is the freezing point of water at standard atmospheric pressure.
- 100°C is the boiling point of water at standard atmospheric pressure.

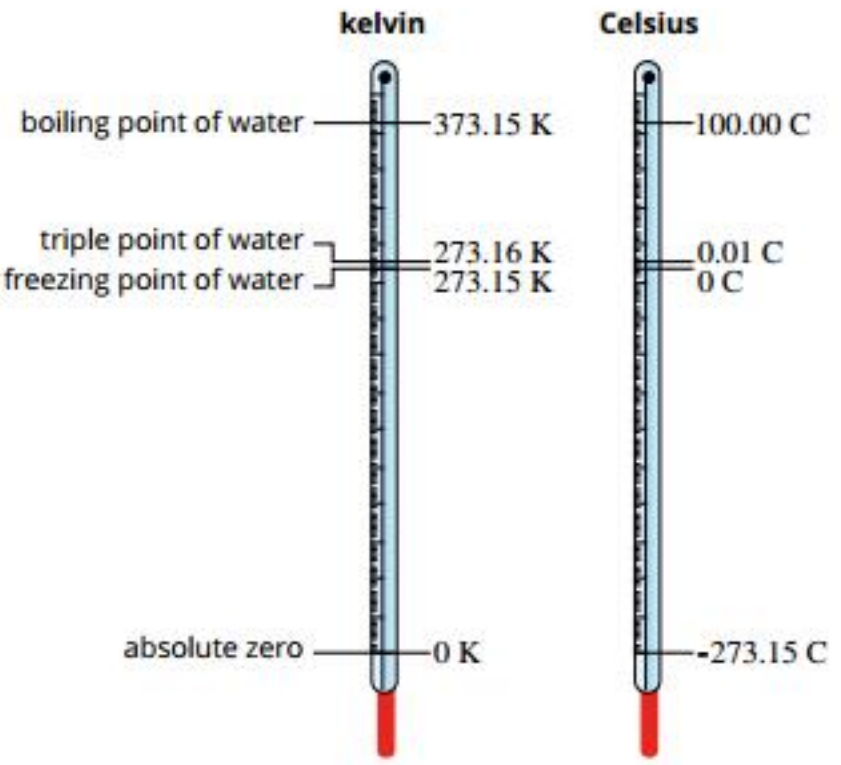


FIGURE 2.2.2 Comparison of the kelvin and Celsius scales; note that there are no negative values on the kelvin scale.

To convert temperatures between degrees Celsius and kelvin:

$T_K = T_C + 273$

SKILLBUILDER

Converting temperature units between kelvin and degrees Celsius

The standard (SI) unit for measuring temperature is the kelvin. However, in our day-to-day lives, we commonly use the Celsius scale. So, it is important to be able to convert values from one unit to the other.

To convert a temperature in degrees Celsius, T_C, to a temperature in kelvin, T_K, add 273:

$T_K = T_C + 273$

Converting from degrees Celsius to kelvin

The boiling point of ethanol is 78°C

To convert a temperature from degrees Celsius to kelvin, add 273.

$T_K = T_C + 273$

$78°C = 78 + 273\,K$

$= 351\,K$

Converting from kelvin to degrees Celsius

Polyethylene, used to make plastic bottles and bags, has a melting point of approximately 393 K.

To convert a temperature from kelvin to degrees Celsius, subtract 273.

$T_C = T_K - 273$

$393\,K = 393 - 273°C$

$= 120°C$

Worked example 2.2.1

CONVERTING TEMPERATURE UNITS

Convert the following temperatures.

a 450°C into K

Thinking	Working
State the relationship between degrees Celsius and kelvin.	$T_K = T_C + 273$
Substitute in the values to convert from °C into K.	$T_K = 450 + 273$ $= 723\,K$

b 189 K into °C

Thinking	Working
State the relationship between degrees Celsius and kelvin.	$T_C = T_K - 273$
Substitute in the values to convert from K into °C.	$T_C = 189 - 273$ $= -84°C$

➤ Try yourself 2.2.1

CONVERTING TEMPERATURE UNITS

Convert the following temperatures.

a −20°C into K

b 654 K into °C

Absolute zero

Experiments indicate that there is a limit to how cold things can get. The kinetic theory suggests that when a given quantity of gas is cooled, its volume decreases. The volume can be plotted against temperature and results in a straight-line graph, as shown in Figure 2.2.3. These experiments were conducted for many different gases and they all result in the same temperature when the graph is extrapolated to zero volume. For every ideal gas, zero volume is at −273.15°C. At 0 K, therefore, the internal motion of the particles in an ideal gas is zero, as is the volume.

Changing temperature

The temperature of a substance is a measure of the average kinetic energy of the molecules it contains. To increase the temperature of an object, you need to increase the average kinetic energy of its molecules. When an object is heated, extra energy is added to the molecules of the object, increasing their kinetic energy. The increase in kinetic energy when heating a substance applies only when a phase change is not taking place (see Module 2.5).

To cool an object, the average kinetic energy needs to decrease. One way to remove kinetic energy from an object is to put it in contact with a colder object. The heat will flow from the hotter object to the colder object, cooling the hotter object as it shares its thermal energy. The flow of heat will be explored in Module 2.3.

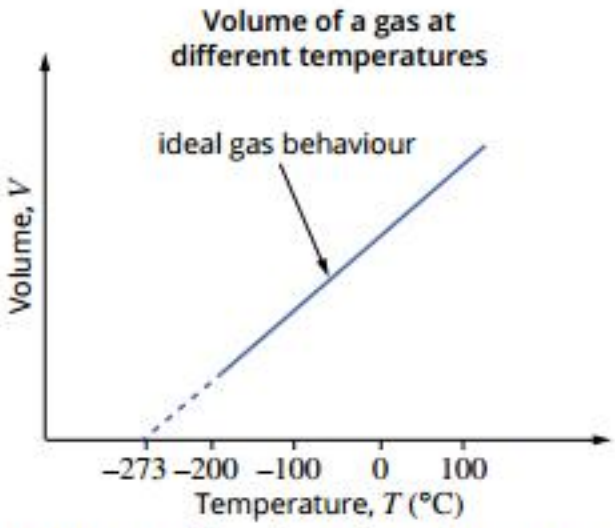


FIGURE 2.2.3 The volume of a gas decreases as the gas cools. This relationship is linear. Extrapolating (extending) the line for any substance to where the volume is zero gives a theoretical value of absolute zero.

2.2 Review

SUMMARY

- Temperatures can be measured in degrees Celsius (°C) or kelvin (K).
- Absolute zero is called simply 'zero kelvin' (0 K) and it is equal to –273.15°C, often rounded to –273°C.
- The size of each unit, 1°C or 1 K, is the same.
- To convert from degrees Celsius to kelvin, add 273. To convert from kelvin to degrees Celsius, subtract 273.
- A change in temperature is due to the addition or removal of heat from a substance when a phase change is not taking place.

KEY QUESTIONS

Describe

1 Describe how a mercury thermometer measures temperature.

2 Explain the concept of absolute zero temperature and the kelvin scale.

Apply

3 Covert the following temperatures:

- **a** 30.0°C into K
- **b** 375 K into °C
- **c** –78°C into K
- **d** 40 K into °C
- **e** 1200°C into K
- **f** 6000 K into °C
- **g** –437°C into K

4 A tank of pure helium is cooled to its freezing point of –272.2°C. Describe the energy of the helium particles at this temperature.

Analyse

5 Sequence the following temperatures from coldest to hottest:

freezing point of water
100.0 K
absolute zero
–180°C
10.0 K

6 Tank A is filled with hydrogen gas at 0.0°C and another tank, B, is filled with hydrogen gas at 300.0 K. Contrast the average kinetic energy of the hydrogen particles in each tank.

7 What is the temperature of an object that has twice as much thermal energy as an object that is 15°C?

8 Explain how absolute zero temperature was determined. You may need to conduct some internet research to help with this.

2.3 Heat flow

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand conduction, convection and radiation
- explain heat transfers in terms of conduction, convection and radiation.

If two objects at different temperatures are in thermal contact (that is, they can exchange energy via heat processes), then thermal energy will transfer from the hotter object to the cooler object. Figure 2.3.1 shows how, by preventing the chick's thermal contact with the cold ice, this adult can protect the vulnerable penguin offspring.

There are three possible means by which heat can be transferred:

- conduction
- convection
- radiation.

FIGURE 2.3.1 Emperor penguin chicks avoid heat loss through conduction by sitting on the adult's feet. In this way they avoid contact with the ice.

CONDUCTION

Conduction is the process by which heat is transferred without the net movement of particles—atoms or molecules—from one area to another. Particles in one object vibrate less, particles in the other object vibrate more, but no particles move from one object to the other. Conduction can occur within a material or between materials that are in thermal contact. For example, if one end of a steel rod is placed in a fire, heat will travel along the rod so that the far end of the rod will also heat up. If a person holds an ice cube, then heat will travel from their hand to the ice.

All materials will conduct heat to some extent, but this process is most significant in solids. Conduction is important in liquids and plays a lesser role in the movement of energy in gases.

Conductors and insulators

Materials that conduct heat readily are referred to as good thermal **conductors**. Materials that are poor thermal conductors are referred to as **insulators**. An example of a good conductor and a good insulator can be seen in Figure 2.3.2.

In secondary physics, the terms 'conductor' and 'insulator' are used in the context of both electricity and heating processes. What makes a material a good conductor of heat does not necessarily make it a good conductor of electricity. The two types of conduction are related but it is important not to confuse the two processes. A material's ability to conduct heat depends on how conduction occurs within the material.

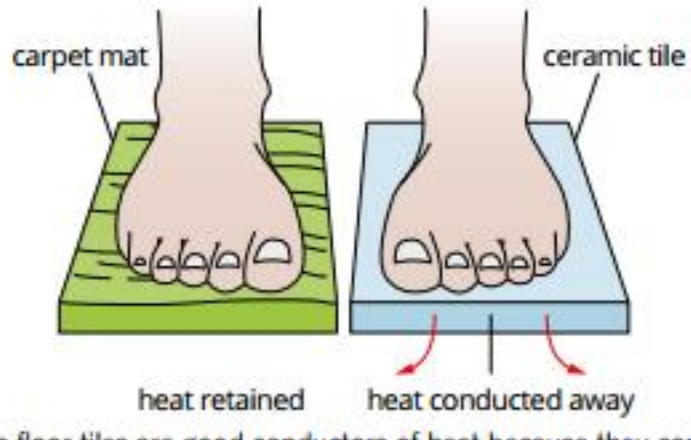


FIGURE 2.3.2 Ceramic floor tiles are good conductors of heat because they conduct heat away from the foot, so the tiles feel cold to your feet. The carpet mat is a thermal insulator because thermal energy from the foot is not transferred away as quickly, so the carpet does not feel as cold to your feet.

Conduction can happen in two ways:

- **by energy transfer through molecular or atomic collisions**
- **by energy transfer by free electrons.**

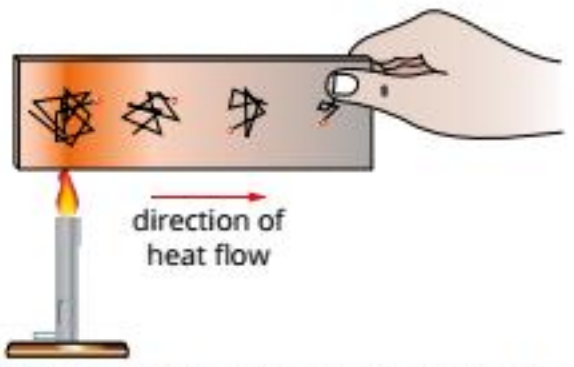


FIGURE 2.3.3 Thermal energy is passed on by collisions between adjacent particles.

Thermal transfer by collision

The kinetic particle model explains that particles in a solid substance are constantly vibrating within the material structure and so interact with neighbouring particles. If one part of the material is heated, then the particles in that region will vibrate more rapidly. Interactions with neighbouring particles will pass on this kinetic energy throughout the system via the bonds between the particles (Figure 2.3.3).

Heat transfer by collision is a slow process because the mass of the particles is relatively large and the vibrational speeds are fairly low. This method of conduction is used for heat transfer in poor conductors of heat (thermal insulators) such as glass, wood and paper.

Thermal transfer by free electrons

Some materials, particularly metals, have electrons that are not directly involved in any one specific chemical bond. Therefore, these electrons are free to move throughout the lattice of positive ions. These free electrons can carry heat through the material.

For example, if a metal is heated, then not only will the positive ions within the metal gain extra energy but so will these free electrons. As the electron's mass is considerably less than that of the positive ions, even a small energy gain will result in a very large gain in speed. Consequently, these free electrons provide a means by which heat can be quickly transferred throughout the whole of the material. It is therefore no surprise that metals, which are good electrical conductors because of these free electrons, are also good thermal conductors.

Thermal conductivity

Thermal conductivity describes the ability of a material to conduct heat. It is temperature dependent and is measured in watts per metre kelvin ($W\,m^{-1}\,K^{-1}$). Table 2.3.1 highlights the difference in conductivity between metals and other substances.

TABLE 2.3.1 Thermal conductivities of some common materials

Material	Conductivity ($W\,m^{-1}\,K^{-1}$)
silver	420
copper	380
aluminium	240
steel	60
ice	2.2
brick, glass	≈ 1
concrete	≈ 1 (depending on composition)
water	0.6
human tissue	0.2
wood	0.15
polystyrene	0.08
paper	0.06
fibreglass	0.04
air	0.025

Factors that affect thermal conductivity

The rate at which heat is transferred is measured in joules per second (Js^{-1}), or watts (W). The rate at which heat will be transferred through a system is dependent on:

- the nature of the material. The larger a material's thermal conductivity, the more rapidly it will conduct heat energy.
- the temperature difference. A greater temperature difference between the two objects will result in a faster rate of energy transfer.

- the thickness of the material. Thicker materials require a greater number of collisions between particles or movement of electrons to transfer energy from one side to the other.
- the surface area. Increasing the surface area relative to the volume of a system increases the number of particles involved in the transfer process, increasing the rate of conduction.

CONVECTION

Convection is the transfer of thermal energy within a fluid (liquid or a gas) by the movement of hot areas from one place to another. Unlike other forms of heat transfer, such as conduction and radiation, convection involves the mass movement of particles within a system over a considerable distance.

Heating by convection

Although liquids and gases are generally not good conductors of thermal energy, heat can be transferred quite quickly through liquids and gases by convection.

As a fluid is heated, its particles gain kinetic energy and push apart due to the increased vibration of the particles. This causes the density of the heated fluid to decrease and the heated fluid rises. Colder fluid, with slower moving particles, is more dense and heavier and therefore falls, moving in to take the place of the warmer fluid. A convection current forms when there is warm fluid rising and cool fluid falling. This action can be seen in Figure 2.3.4. Upwellings in oceans, wind and weather patterns are at least partially due to convection on a very large scale.

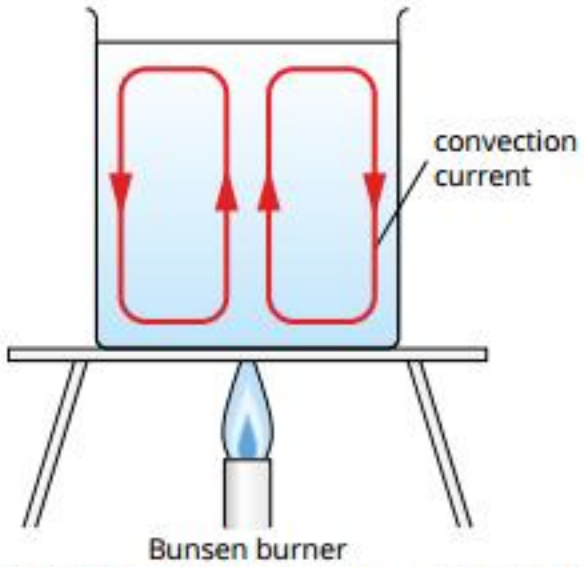


FIGURE 2.3.4 When a liquid or gas is heated, it becomes hotter and less dense so will rise. The colder, denser fluid will fall. As this fluid heats up, it in turn will rise, creating a convection current.

Factors that affect thermal convection

It is difficult to quantify the thermal energy transferred via convection, but some estimates can be made. The rate at which convection will occur is affected by:

- the temperature difference between the heat source and the convective fluid
- the surface area exposed to the convective fluid.

In a container, the effectiveness of convection to transfer heat depends on the placement of the source of heat. For example, the heating element in a kettle is always found near the bottom of the kettle. From this position, convection currents form throughout the water to heat it more effectively (Figure 2.3.5a). If the heating element is placed near the top of the kettle, convection currents form only near the top. This is because the hotter water is less dense than the cooler water below and will remain near the top. Convection currents will not form throughout the water (Figure 2.3.5b).

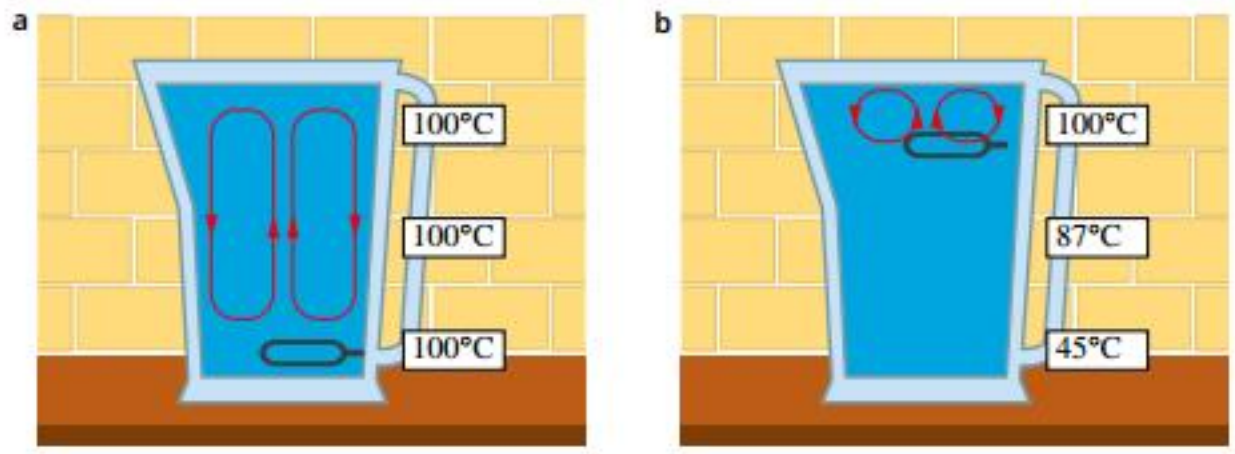


FIGURE 2.3.5 (a) By placing the heating element at the bottom of a kettle, the water near the bottom is heated and rises, forming convection currents throughout the entire depth of the water. (b) If the heating element is placed near the top of the kettle, the convection currents form near the top and heat transfer is slower.

To visualise convection currents, set up a glass beaker with one side positioned over a Bunsen burner. Fill the beaker with water and add a couple of drops of food colouring. The convection patterns in the water will be highlighted and make a great photograph, as shown in Figure 2.3.6 on page 18.

FIGURE 2.3.6 Demonstration of convection using a Bunsen burner, water and food colouring

Applications of convection

There are two main causes of convection:

- forced convection, in which heat transfer is caused by an external source. An example is ducted heating in which air is heated and then blown into a room. Applications of forced convection are considered when designing heating and cooling systems.
- natural convection, in which heat transfer is induced by different temperature gradients of fluids in nature. Ocean currents are an example of natural convection.

A dramatic example of natural convection is the thunderhead clouds of summer storms (Figure 2.3.7), which form when hot, humid air from natural convection currents is carried rapidly upwards into the cooler upper atmosphere.

FIGURE 2.3.7 The thunderheads of summer storms are a very visible indication of natural convection in action.

Paragliders fly by sitting in a harness suspended beneath a fabric wing (Figure 2.3.8). They gain altitude by catching thermals. Thermals are columns of rising hot air created by dark regions on the ground that have been heated up by the Sun. Roads, rock faces and ploughed fields are good at creating thermals.

FIGURE 2.3.8 Paragliders can gain altitude by finding a thermal. Thermals are areas of rising hot air created by hot regions on the ground.

RADIATION

Both convection and conduction involve the transfer of heat through matter. Life on Earth depends upon the transfer of energy from the Sun through the near-vacuum of space. If heat could only be transferred by the action of particles, then the Sun's energy would never reach Earth. Radiation is a means of transfer of heat without the movement of matter.

Electromagnetic radiation

In this context, **radiation** is a shortened form of electromagnetic radiation, which includes visible, ultraviolet and infrared light. Together with other forms of light, these make up the **electromagnetic spectrum**.

Heat is transferred from one place to another without the movement of particles by electromagnetic radiation (light). Electromagnetic radiation travels at the speed of light. When electromagnetic radiation hits an object, it will be partially reflected, partially transmitted and partially absorbed. The absorbed radiation transfers thermal energy to the absorbing object and causes a rise in temperature. When you hold a marshmallow by an open fire, you are using a combination of radiation and convection to toast the marshmallow (Figure 2.3.9).

FIGURE 2.3.9 Heat transfer from the flame to the marshmallow is an example of radiation.

Electromagnetic radiation is emitted by all objects that are at a temperature above absolute zero (0K or −273°C). The **wavelength** and **frequency** of the emitted radiation depend on the internal energy of the object. The higher the temperature of the object, the higher the frequency and the shorter the wavelength of the radiation emitted. The total radiant energy emitted increases as the temperature of the system increases. This can be seen in Figure 2.3.10.

A human body emits radiation in the infrared range of wavelengths, whereas hotter objects emit radiation of a higher frequency and shorter wavelength. Hotter objects can emit radiation in the range of visible, ultraviolet and shorter wavelengths of the electromagnetic spectrum. For example, as a red-hot fire poker heats up further, it becomes yellow-hot. Wavelengths that you feel as warm tend to be below 9.5 μm.

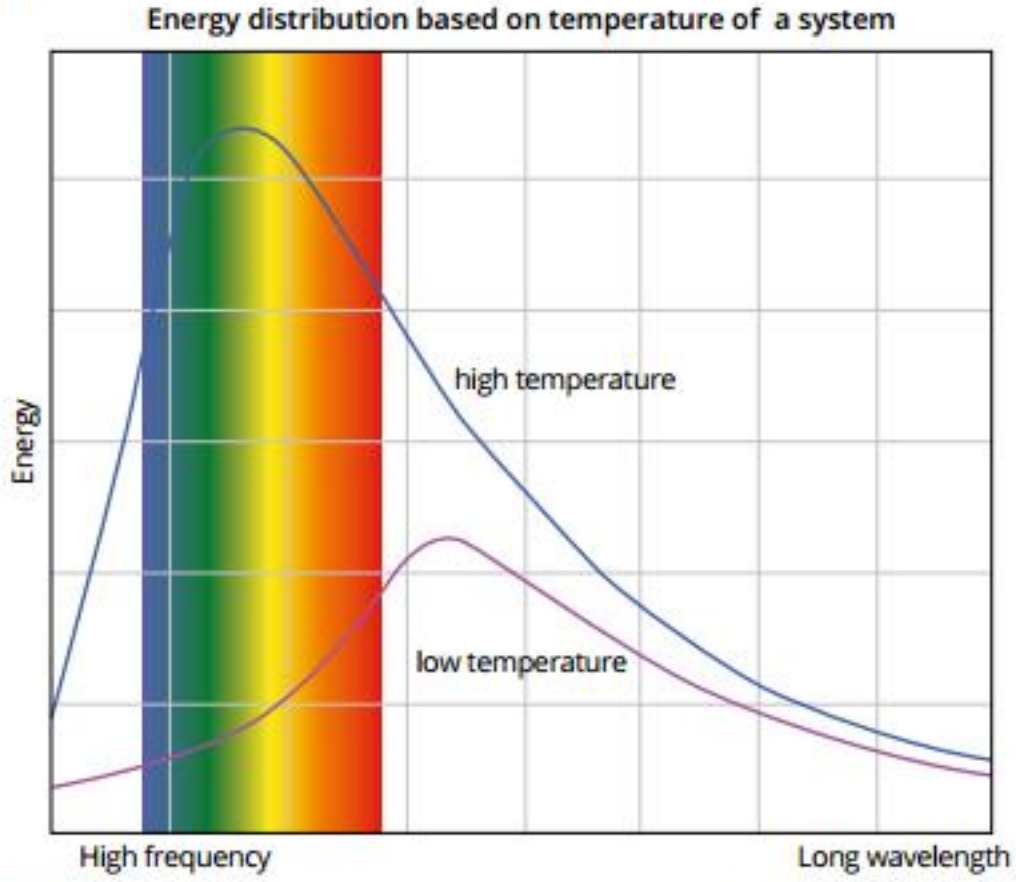


FIGURE 2.3.10 A system emits radiation over a range of frequencies. At a low temperature, it will emit small amounts of radiation of longer wavelengths. As the temperature of the system increases, more short-wavelength radiation is emitted and the total radiant energy emitted increases.

Absorption and emission of radiant energy

All objects both absorb and emit thermal energy by radiation. If an object absorbs more thermal energy than it emits, its temperature will increase. If an object emits more energy than it absorbs, its temperature will decrease. If no temperature change occurs, the object and its surroundings are in thermal equilibrium.

All objects emit some radiation, but they will not all emit or absorb at the same rate. Several factors affect both the rate of **emission** and the rate of **absorption**.

- Surface area: the larger the exposed surface area, the higher the rate of radiant transfer.
- Temperature: the greater the difference between the temperature of the absorbing or emitting surface and the temperature of its surroundings, the greater the rate of energy transfer by radiation.
- Wavelength of the **incident** radiation: matte black surfaces are almost perfect absorbers of radiant energy at all wavelengths. Highly reflective surfaces are good reflectors of all wavelengths. An example of how reflective surfaces can be exploited is shown in Figure 2.3.11. For all other surfaces, the absorption of particular wavelengths of radiant energy will be affected by the wavelength of that energy. For example, white surfaces absorb visible wavelengths of radiant energy poorly, but they will absorb infrared radiation just as well as black surfaces do.
- Surface colour and texture: the characteristics of the surface itself determine how readily that surface will emit or absorb radiant energy. Matte black surfaces will absorb and emit radiant energy faster than shiny, white surfaces. This means that a roughened, dark surface will heat up faster than a shiny, light surface. Matte black objects will also cool down faster because they will radiate energy just as efficiently as they absorb it. Car radiators are painted black to increase the emission by radiation of the thermal energy that is collected from the car engine.

FIGURE 2.3.11 The silvered surface of an emergency blanket reflects thermal energy back to the body and retains the radiant energy, which would normally be lost. This simple method works as excellent thermal insulation.

2.3 Review

SUMMARY

- Conduction is the process of heat transfer within a material or between materials without the overall transfer of the substance itself.
- All materials will conduct heat to a greater or lesser degree. Materials that readily conduct heat are called good thermal conductors. Materials that conduct heat poorly are called thermal insulators.
- The rate of conduction depends on the temperature difference between two materials, the thickness of the material, the surface area and the nature of the material.
- Convection is the transfer of heat within a fluid (liquid or gas).
- Convection involves the mass movement of particles within a system over a distance.
- A convection current forms when there is warm fluid rising and cool fluid falling.
- Any object whose temperature is greater than absolute zero emits thermal energy by radiation.
- Radiant transfer of thermal energy from one place to another occurs by means of electromagnetic waves.
- When electromagnetic radiation falls on an object, it will be partially reflected, partially transmitted and partially absorbed.
- The rate of emission or absorption of radiant heat will depend on the:
  - temperature difference between the object and the surrounding environment
  - surface area and surface characteristics of the object
  - wavelength of the radiation.

KEY QUESTIONS

Describe

1 List the properties of a material that affect its ability to conduct heat.

2 List the states of matter in which convection can occur.

3 What is the initial direction of the transfer of heat in a convection current?

4 Describe how we feel heat transferred from a fire.

Apply

5 Explain why the process of conduction by molecular collision is slow.

6 Pilots of glider aircraft or hang-gliders, some birds — such as eagles — and some insects rely on 'thermals' to give them extra lift. Explain how these rising columns of air are established.

7 Explain how a down(feather)-filled quilt keeps a person warm in winter.

8 Why is the vacuum of space a good insulator?

Analyse

9 On a cold day, the plastic or rubber handles of a bicycle feel much warmer than the metal surfaces. Explain this in terms of the thermal conductivity of each material.

10 Convection is referred to as a method of heat transfer through fluids. Evaluate whether it is possible for solids to pass on their heat energy by convection.

11 On a hot day, the top layer of water in a swimming pool can heat up while the lower, deeper parts of the water can remain quite cold. Explain, using the concept of convection, why this happens.

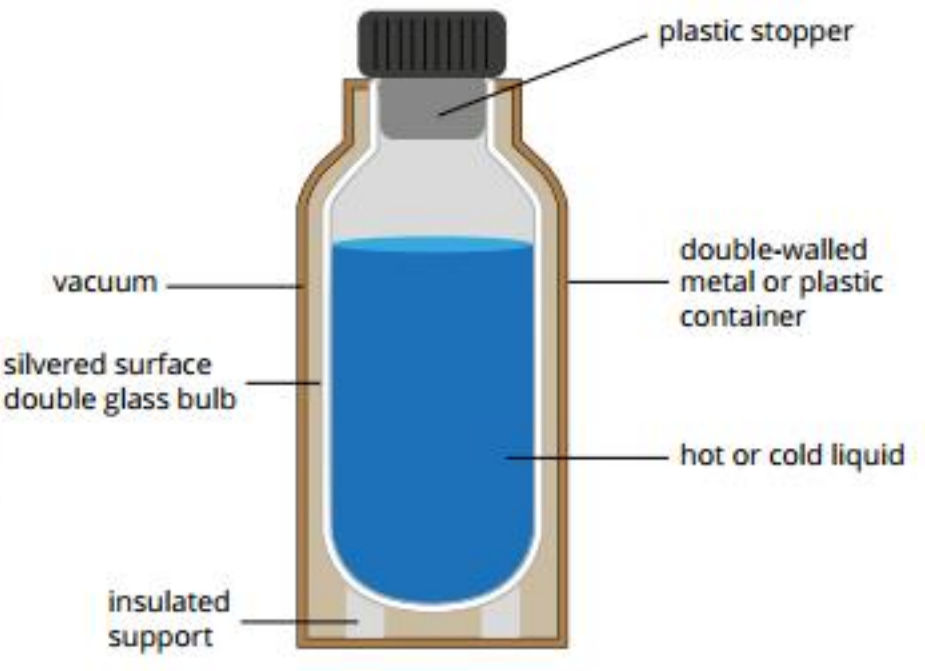
12 Three identical, sealed beakers are filled with near-boiling water. One beaker is matte black, one is dull white and the third is gloss white.

a Predict which beaker will cool fastest.

b Predict which beaker will cool slowest.

13 A vacuum flask has a tight-fitting stopper at the top. The double glass bulb has silvered inner surfaces and has had most of the air evacuated from it. It is located inside a protective outer case with insulated supports. Assess how this design makes a vacuum flask good at keeping liquids hot inside.

Vacuum or Dewar flask



2.4 Specific heat capacity

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that the amount of energy required to raise the temperature of a substance depends on the mass of the substance
- understand that the amount of energy required to raise the temperature of a substance depends on what substance it is
- understand that the amount of energy required to raise the temperature of a substance depends on the state of the substance
- analyse, compare and predict the amount of energy required to raise the temperature of a substance
- understand the concept of specific heat capacity.

A small volume of water in a kettle will experience a greater change in temperature than a larger volume, if heated for the same time. A metal object left in the sunshine gets hotter faster than a wooden object. Large heaters warm rooms faster than small heaters.

These simple observations suggest that the mass, material and amount of energy transferred influence any change of temperature.

CHANGING TEMPERATURE OF A SUBSTANCE

The temperature of a substance is a measure of the average kinetic energy of the particles inside the substance. To increase the temperature of the substance, the kinetic energy of its particles must increase. This happens when heat is transferred to that substance. The amount the temperature increases for a given amount of heat energy, depends on the type of substance and its mass.

The internal structure of a substance determines its **specific heat capacity**, c, which is a measure of how easy it is to heat it up. More precisely, the specific heat capacity of a substance is the amount of energy that must be transferred to change the temperature of the material by 1°C or 1 K. It has the units $Jkg^{-1}K^{-1}$ or $Jkg^{-1}°C^{-1}$. The specific heat capacity of a material changes when the material changes state. For a given material, therefore, you can calculate how much heat energy is needed to raise the temperature by a given amount using the specific heat capacity, provided a change of state does not occur.

Table 2.4.1 lists the specific heat capacities for some common materials. Included in the list is the average value for the human body, which considers the various materials within the body and the proportion that each material contributes to the body's total mass.

TABLE 2.4.1 Approximate specific heat capacities of common substances

Material	c ($Jkg^{-1}K^{-1}$)
lead	130
mercury	140
brass	370
copper	390
iron	440
glass	840
aluminium	900
air	1000
steam (water)	2000
ice (water)	2100
ethanol	2460
methylated spirits	2500
human body	3500
liquid water	4200

The specific heat capacity of a material, c, is the amount of energy that must be transferred to change the temperature of 1 kg of the material by 1°C or 1 K.

Heat energy is calculated from the specific heat capacity for a given temperature change by using the equation:

$Q = mc\Delta T$

where

Q is the heat energy transferred in joules (J)

m is the mass in kilograms (kg)

c is the specific heat capacity of the material ($J\,kg^{-1}\,K^{-1}$)

ΔT is the change in temperature (°C or K).

Worked example 2.4.1

CALCULATIONS USING SPECIFIC HEAT CAPACITY

A hot water tank contains 135 L of water. Initially, the water is at 20.0°C. Calculate the amount of energy that must be transferred to the water to raise the temperature to 70.0°C.

Thinking	Working
Calculate the mass of water. 1 L of water = 1 kg	Volume = 135 L Mass = 135 kg
ΔT = final temperature – initial temperature	$\Delta T = 70.0 - 20.0$ $= 50.0°C$
From Table 2.4.1 on page 21: $c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$. Use the equation $Q = mc\Delta T$.	$Q = mc\Delta T$ $= 135 \times 4200 \times 50.0$ $= 28\,350\,000\,J$ $= 28.4\,MJ$

➤ Try yourself 2.4.1

CALCULATIONS USING SPECIFIC HEAT CAPACITY

A bath contains 75 L of water. Initially, the water is at 50.0°C. Calculate the amount of energy that must be transferred from the water to cool the bath to 30.0°C.

Worked example 2.4.2

COMPARING SPECIFIC HEAT CAPACITIES

Different states of matter of the same substance have different specific heat capacities. Calculate the ratio of the specific heat capacity of liquid water to that of ice.

Thinking	Working
See Table 2.4.1 on page 21 for the specific heat capacities of water in different states.	$c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$ $c_{ice} = 2100\,J\,kg^{-1}\,K^{-1}$
Divide the specific heat of water by the specific heat of ice. Note that ratios have no units because the units of the two quantities are the same and cancel out.	$\text{Ratio} = \frac{c_{water}}{c_{ice}}$ $= \frac{4200}{2100}$ $= 2$

➤ Try yourself 2.4.2

COMPARING SPECIFIC HEAT CAPACITIES

Calculate the ratio of the specific heat capacity of liquid water to that of steam.

SPECIFIC HEAT CAPACITY OF WATER

Note the high specific heat capacity of water in Table 2.4.1. It is about 10 times higher than that of most metals listed. In fact, the specific heat capacity of water is higher than those of most common materials. As a result, water makes a very useful cooling and heat storage agent and is used in areas such as generator cooling towers and car-engine radiators.

Life on Earth also depends on the specific heat capacity of water. About 70% of the Earth's surface is covered by water and these water bodies can absorb large quantities of thermal energy without great changes in temperature. Oceans both heat up and cool down more slowly than the land areas next to them. This helps to maintain a relatively stable range of temperatures for life on Earth.

Scientists are now monitoring the temperatures of the deep oceans to determine how the ability of oceans to store large amounts of energy might affect climate change. More than 90% of the excess heat trapped in Earth's atmosphere—due to human-caused global warming—is trapped in the oceans.

2.4 Review

SUMMARY

- The specific heat capacity, c, of a substance is a measure of the amount of energy that must be transferred to change the temperature of 1 kg of material by 1°C or 1 K. Its units are $J\,kg^{-1}\,K^{-1}$.
- A substance will have different specific heat capacities in different states (solid, liquid, gas).
- When heat is transferred to or from a system or object, the temperature change depends upon the amount of energy transferred, the mass of the material(s) and the specific heat capacity of the material(s): $Q = mc\Delta T$.

KEY QUESTIONS

Describe

1 Equal masses of water and aluminium are heated through the same temperature range. Identify the material that requires the most energy to achieve this result. ($c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$, $c_{aluminium} = 900\,J\,kg^{-1}\,K^{-1}$)

2 Determine which has more thermal energy: 10.0 kg of iron at 20.0°C or 10.0 kg of aluminium at 20.0°C. ($c_{iron} = 440\,J\,kg^{-1}\,K^{-1}$, $c_{aluminum} = 900\,J\,kg^{-1}\,K^{-1}$)

Apply

3 100.0 mL of water is heated to change its temperature from 15.0°C to 20.0°C. Calculate how much energy is transferred to the water to achieve this temperature change. ($c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$)

4 15 400 J of heat energy is transferred to a 12 kg block of iron. Calculate the temperature increase of the iron. ($c_{iron} = 440\,J\,kg^{-1}\,K^{-1}$)

5 A piece of glass is heated with 2688 J of energy. How much glass needs to be heated for a temperature change of 5.00 K? ($c_{glass} = 840\,J\,kg^{-1}\,K^{-1}$)

Analyse

6 The specific heat capacity of sand is $830\,J\,kg^{-1}\,K^{-1}$. Explain why at the beach on a hot day the sand feels so much hotter than the water. ($c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$)

7 If 4.0 kJ of energy is required to raise the temperature of 1.0 kg of paraffin by 2.0°C, calculate how much energy (in kJ) is required to raise the temperature of 5.0 kg of paraffin by 1.0°C.

2.5 Phase changes and specific latent heat

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand changes of state
- understand specific latent heat
- calculate the energy required to change a substance's state
- interpret a phase change diagram.

If water is heated, its temperature will rise. If enough energy is transferred to the water, eventually the water will boil. The water changes state (from liquid to gas). The **specific latent heat** is the energy released or absorbed during a change of state. Latent means hidden or unseen. While a substance is in the process of changing state, its temperature remains constant. For example, the energy used when ice melts into water is 'hidden' in the sense that the temperature does not rise while the change of state is occurring.

ENERGY AND CHANGE OF STATE

Look at the example of a heating graph for water shown in Figure 2.5.1. In this experiment, heat energy is added at a constant rate, but the increase in the temperature of the water is not always constant. In some sections, the temperature increases at a constant rate, but in other sections the temperature remains unchanged (the horizontal sections). In the sections of constant temperature, the material is changing state. The temperature remains constant during the change in state from ice to liquid water and again from liquid water to steam.

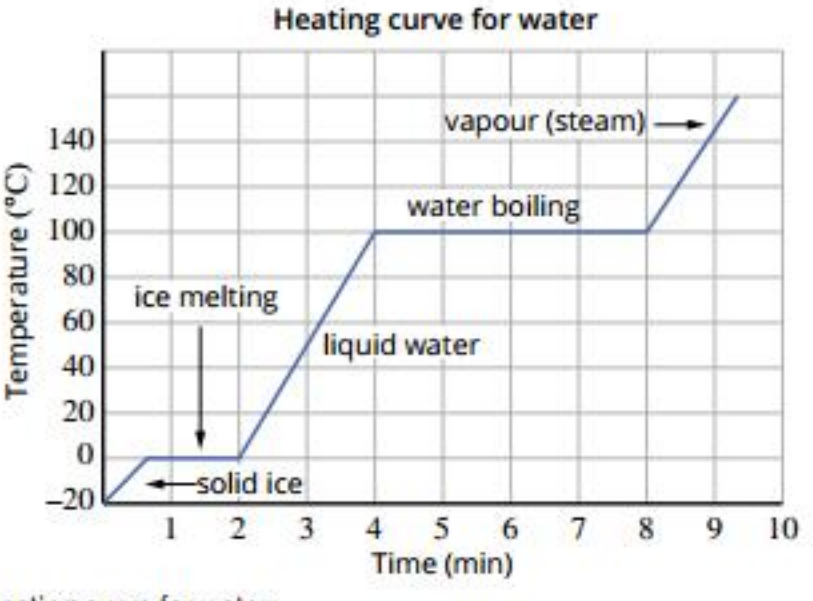


FIGURE 2.5.1 A heating curve for water

i The specific latent heat is calculated using the equation:

$Q = mL$

where

Q is the heat energy transferred in joules (J)

m is the mass in kilograms (kg)

L is the specific latent heat ($J\,kg^{-1}$).

SPECIFIC LATENT HEAT

The energy needed to change the state of a substance (e.g., solid to liquid, liquid to gas) is called specific latent heat. Specific latent heat is the 'hidden' energy that has to be added or removed from a material in order for the material to change state. The energy required, Q, to change the state of a substance of mass m can be calculated using the specific latent heat of the substance, L.

$$Q = mL$$

Specific latent heat of fusion (melting)

The temperature of a solid increases as thermal energy is transferred to the solid. The particles within the solid gain internal energy (as kinetic energy and some potential energy) and their speed of vibration increases. At the point where the solid begins to melt, the particles move further apart, reducing the strength of the bonds holding them in place. At this point, instead of increasing the temperature, the extra energy increases the potential energy of the particles, reducing the interparticle or intermolecular forces. No change in temperature occurs because all the extra energy supplied is used in reducing these forces between particles.

The amount of energy required to melt a solid is the same as the amount of potential energy released when the liquid re-forms into a solid. It is termed the **specific latent heat of fusion**.

The amount of energy required will depend on the solid. The energy required, Q, to change a solid of mass m to a liquid can be calculated using the specific latent heat of fusion, L_{fusion}.

$$Q = mL_{fusion}$$

It takes almost 80 times as much energy to turn 1 kg of ice into water (with no temperature change) as it does to raise the temperature of 1 kg of water by 1°C. It takes a lot more energy to overcome the large intermolecular forces within the ice than it does to simply add kinetic energy in raising the temperature. The specific latent heats of fusion for some common materials are listed in Table 2.5.1.

For a given mass of a substance:
Heat energy transferred = mass of substance × specific latent heat of fusion

$$Q = mL_{fusion}$$

TABLE 2.5.1 The specific latent heats of fusion for some common materials

Substance	Melting point (°C)	L_{fusion} (J kg^{-1})
silver	961	0.88×10^5
oxygen	−219	0.14×10^5
lead	327	0.25×10^5
ethanol	−114	1.05×10^5
water	0	3.34×10^5

Worked example 2.5.1

SPECIFIC LATENT HEAT OF FUSION

Calculate how much energy must be removed from 2.50 L of water at 0.0°C to produce a block of ice at 0.0°C. Express your answer in kJ.

Thinking	Working
Cooling from liquid to solid involves the specific latent heat of fusion, as the energy is removed from the water. Calculate the mass of water involved. 1 L of water = 1 kg	2.50 L = 2.50 kg
Use Table 2.5.1 to find the specific latent heat of fusion for water.	$L_{fusion} = 3.34 \times 10^5$ J kg^{-1}
Use the equation: $Q = mL_{fusion}$	$Q = mL_{fusion}$ $= 2.50 \times 3.34 \times 10^5$ $= 8.35 \times 10^5$ J
Convert to kJ.	840 kJ of energy is removed.

➤ Try yourself 2.5.1

SPECIFIC LATENT HEAT OF FUSION

Calculate how much energy must be removed from 5.5 kg of liquid lead at 327°C to produce a block of solid lead at 327°C. Express your answer in kJ.

Specific latent heat of vaporisation (boiling)

It takes much more energy to convert a liquid to a gas than it does to convert a solid to a liquid. This is because, to convert to a gas, the intermolecular bonds must be broken. During the change of state, the energy supplied is used solely in overcoming the intermolecular bonds. The temperature will not rise until all of the material in the liquid state is converted to a gas, assuming that the liquid is evenly heated. For example, when liquid water is heated to boiling point, a large amount of energy is required to change its state from liquid to steam (gas). The temperature will remain at 100°C until all of the water has turned into steam. Once the water is completely converted to steam, then the temperature can start to rise again.

The amount of energy required to change a liquid to a gas is the same as the potential energy released when the gas returns to a liquid. It is called the **specific latent heat of vaporisation**.

The amount of energy required will depend on the substance. The energy required, Q, to change a liquid of mass m to a gas can be calculated using the specific latent heat of vaporisation, L_{vapour}.

$$Q = mL_{vapour}$$

Note that, in just about every case, the specific latent heat of vaporisation of a substance will be different from the specific latent heat of fusion for that substance. The specific latent heats of vaporisation for some common materials are listed in Table 2.5.2.

In many instances, it is necessary to consider the energy required to heat a substance as well as change its state. Problems like this are solved by considering the rise in temperature separately from the change of state.

> **For a given mass of a substance:**
> Heat energy transferred = mass of substance × specific latent heat of vaporisation
> $Q = mL_{vapour}$

TABLE 2.5.2 The specific latent heat of vaporisation of some common materials

Substance	Boiling point (°C)	L_{vapour} (J kg^{-1})
oxygen	−183	2.2×10^5
ethanol	78	8.7×10^5
lead	1750	9.0×10^5
water	100	22.6×10^5
silver	2193	23.0×10^5

Worked example 2.5.2

CHANGE IN TEMPERATURE AND STATE

50.0 mL of water is heated from a room temperature of 20.0°C to its boiling point at 100.0°C. The water is boiled at this temperature until it has completely evaporated. Calculate how much energy in total was required to raise the temperature and boil the water.

Thinking	Working
Calculate the mass of water involved. 1 L of water = 1 kg	50.0 mL of water = 0.050 kg
Find the specific heat capacity of water from Table 2.4.1 on page 21.	$c = 4200\,J\,kg^{-1}\,K^{-1}$
Use the equation $Q = mc\Delta T$ to calculate the heat energy required to change the temperature of water from 20°C to 100°C.	$Q = mc\Delta T$ $= 0.050 \times 4200 \times (100.0 - 20.0)$ $= 16800\,J$
Find the specific latent heat of vaporisation of water from Table 2.5.1 on page 25.	$L_{vapour} = 22.6 \times 10^5\,J\,kg^{-1}$
Use the equation $Q = mL_{vapour}$ to calculate the heat energy required to boil water.	$Q = mL_{vapour}$ $= 0.05 \times 22.6 \times 10^5$ $= 113000\,J$
Find the total energy required to raise the temperature and change the state of the water.	Total $Q = 16800 + 113000$ $= 1.30 \times 10^5\,J$ $= 130\,kJ$

➤ Try yourself 2.5.2

CHANGE IN TEMPERATURE AND STATE

3.0 L of water is heated from a fridge temperature of 4.0°C to its boiling point at 100.0°C. The water is boiled at this temperature until it has completely evaporated. Calculate how much energy in total was required to raise the temperature and boil the water.

EVAPORATION AND COOLING

If you spill some water on the floor then come back in a couple of hours, the water will probably be gone. It will have evaporated. It has changed from a liquid into a vapour at room temperature in a process called **evaporation**. The reason for this is that the water particles—if they have sufficient energy—can escape through the surface of the liquid into the air. Over time, no liquid remains.

Evaporation is more noticeable in **volatile** liquids such as methylated spirits, mineral turpentine, perfume and liquid paper. The surface bonds are weaker in these liquids and they evaporate rapidly. This is why you should never leave the lids off bottles of these liquids. Volatile liquids are often stored in narrow-necked bottles for this reason.

The rate of evaporation of a liquid can depend on:

- the volatility of the liquid—more-volatile liquids evaporate faster
- the surface area—greater evaporation occurs when greater surface areas are exposed to the air
- the temperature—hotter liquids evaporate faster
- the humidity—less evaporation occurs in more humid conditions
- air movement—if a breeze is blowing over the surface of the liquid, evaporation is more rapid.

Whenever evaporation occurs, higher-energy particles escape the surface of the liquid, leaving the lower-energy particles behind (Figure 2.5.2). As a result, the average kinetic energy of the particles remaining in the liquid decreases and the temperature drops. Humans and many animals use this cooling principle when sweating (perspiring) to stay cool. Since the hotter molecules of perspiration are removed by evaporation, the overall temperature after evaporation is cooler; it is your perspiration evaporating that cools you down. Similarly, when rubbing alcohol is dabbed on your arm before an injection, the cooling of the volatile liquid numbs your skin.

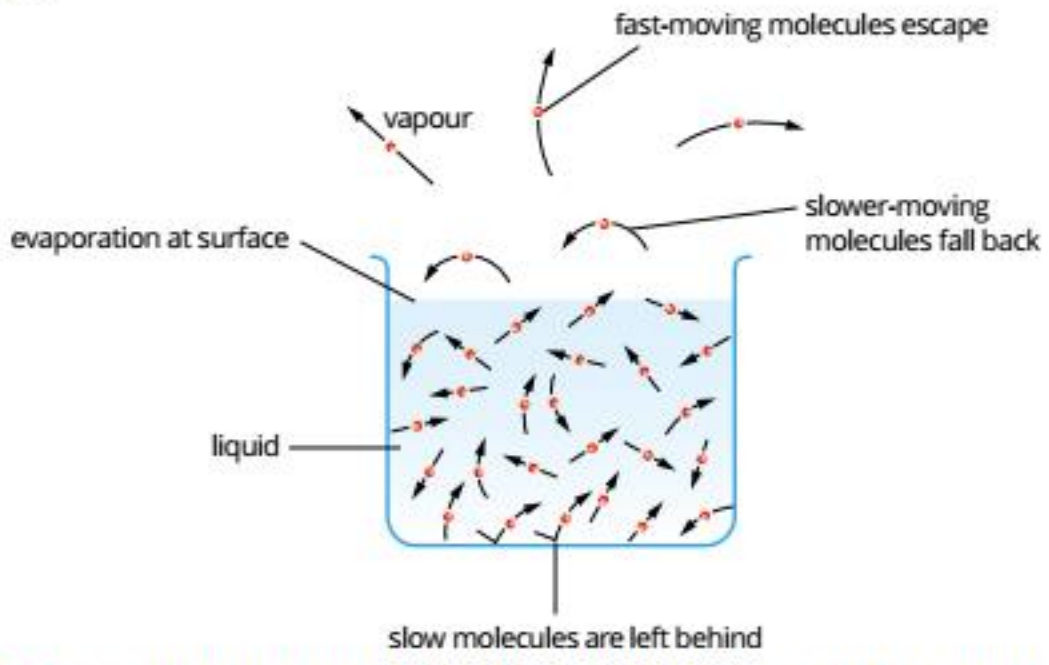


FIGURE 2.5.2 Fast-moving molecules with high kinetic energy can escape the liquid, leaving molecules with lower kinetic energy behind.

HEATING CURVES

Figure 2.5.3 is a heating graph for water. It is also called a phase change diagram. The graph shows the temperature change when a substance is heated at a constant rate and it changes state from a solid to a liquid to a gas. These graphs can provide information on the specific heat capacity of each phase and specific latent heats of fusion and vaporisation of a substance.

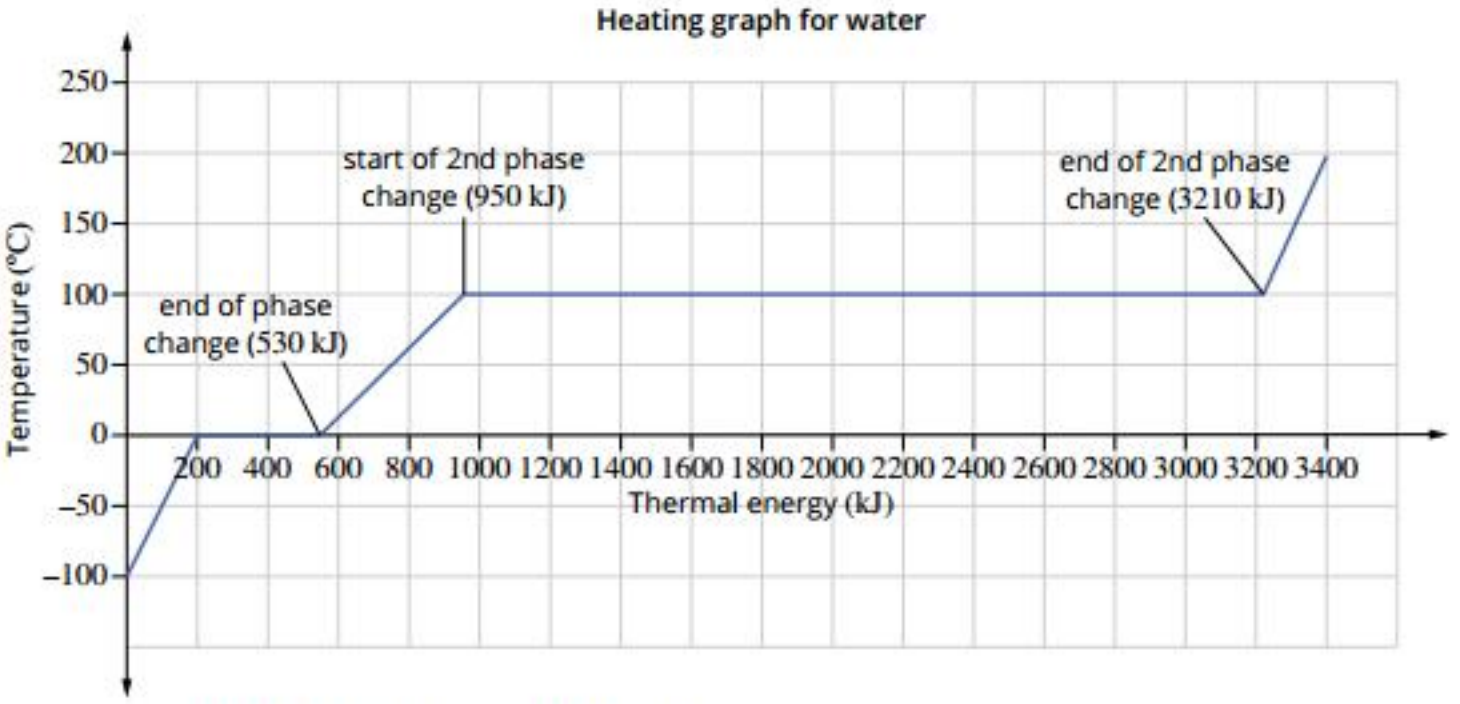


FIGURE 2.5.3 A heating graph for water

Determining specific latent heats from a heating curve

The horizontal sections of the graph represent the phase changes in the substance. The heat energy going into the substance is being used to increase the potential energy and change phase. By determining how much heat energy (Q) is going into a substance for a phase change to occur, the specific latent heat for that phase change can be calculated.

Worked example 2.5.3

DETERMINING SPECIFIC LATENT HEAT OF FUSION USING A HEATING CURVE

1.0 kg of water has been heated from ice through to steam. Use the appropriate section of Figure 2.5.3 to determine the specific latent heat of fusion of water.	
Thinking	**Working**
Find the heat required to change the ice to water. On the graph, the first phase change is from 200 KJ to 530 kJ.	$Q = 530\,\text{kJ} - 200\,\text{KJ}$ $= 330\,\text{kJ}$
Rearrange the equation $Q = mL_{fusion}$ to make L_{fusion} the subject. $Q = 330\,000\,\text{J}$ $m = 1.0\,\text{kg}$	$Q = mL_{fusion}$ $L_{fusion} = \frac{Q}{m}$ $= \frac{330\,000}{1.0}$ $= 330\,000\,\text{J kg}^{-1}$

➤ Try it yourself 2.5.3

DETERMINING SPECIFIC LATENT HEAT OF FUSION USING A HEATING CURVE

1.0 kg of water has been heated from ice through to steam at a temperature of 190°C. Use the appropriate section of Figure 2.5.3 to determine the specific latent heat of vaporisation of water.

Determining specific heat capacities from a heating curve

The sloped sections of the heating graph indicate when a phase (solid, liquid or gas) is undergoing a temperature change. These are the sections where the specific heat capacity applies. From the gradient of the graph (in these sections), the specific heat capacity can be calculated for each phase.

Worked example 2.5.4

DETERMINING SPECIFIC HEAT CAPACITY USING A HEATING CURVE

1.0 kg of water has been heated from ice through to steam. Use the slope of the appropriate section of Figure 2.5.3 to determine the specific heat capacity of water.

Thinking	Working
Find the gradient of the line for the liquid phase.	$\text{Gradient} = \frac{\text{rise}}{\text{run}}$ $= \frac{100}{420\,000}$ $= 23.8 \times 10^{-4}$
For a heating curve, the rise is the change in temperature, ΔT, and the run is the change in energy transferred, ΔQ.	$\text{Gradient} = \frac{\text{rise}}{\text{run}}$ $= \frac{\Delta T}{\Delta Q}$
Rearrange the equation $Q = mc\Delta T$.	$Q = mc\Delta T$ $\frac{\Delta T}{\Delta Q} = \frac{1}{mc}$
The mass is 1.0 kg, so $m = 1$.	The gradient is $\frac{1}{c}$.
Use the gradient and the result that the gradient is $\frac{1}{c}$ to find c.	$\frac{1}{c} = 23.8 \times 10^{-4}$ $Q = \frac{1}{2.38 \times 10^{-4}}$ $= 4200\,\text{J kg}^{-1}\,\text{K}^{-1}$

➤ Try yourself 2.5.4

DETERMINING SPECIFIC HEAT CAPACITY USING A HEATING CURVE

1.0 kg of water has been heated from ice through to steam. Use the slope of the appropriate section of Figure 2.5.3 to determine the specific heat capacity of steam.

2.5 Review

SUMMARY

- When a solid material changes state, energy is needed to separate the particles by overcoming the attractive forces between the particles.
- Specific latent heat is the energy required to change the state of 1 kg of material at a constant temperature.
- In general, for any mass of material the energy required (or released) is $Q = mL$.
- The specific latent heat of fusion, L_{fusion}, is the energy required to change 1 kg of a material between the solid and liquid states.
- The specific latent heat of vaporisation, L_{vapour}, is the energy required to change 1 kg of a material between the liquid and gaseous states.
- The specific latent heat of fusion of a material will be different from (and usually less than) the specific latent heat of vaporisation for that material.

Continued over page

2.5 Review *continued*

- Evaporation is when a liquid turns into gas at room temperature. The temperature of the liquid falls as this occurs.
- The rate of evaporation depends on the volatility, temperature and surface area of the liquid and the presence of air movement.
- A heating curve or phase change diagram shows the change in temperature when a substance is heated at a constant rate and changes from a solid to a liquid to a gas. It can be used to find the specific latent heat and specific heat capacity of a substance.

KEY QUESTIONS

Refer to the values in Table 2.5.1 and Table 2.5.2 on pages 25 and 26. You may also need to refer to Table 2.4.1 on page 21.

Describe

1 State and explain two factors that affect the rate of evaporation of sweat.

2 Describe 'specific latent heat'.

3 What kind of internal energy is associated with a phase change? Describe how this internal energy changes during a phase change.

Apply

4 Explain why the temperature does not change during the boiling phase on a heating curve.

5 Determine the amount of heat energy that must be transferred away from 100.0g of steam at 100.0°C to change it completely to a liquid (at 100.0°C). ($L_{\text{water vapour}} = 22.6 \times 10^5\,\text{J kg}^{-1}$).

6 24 600J of heat energy is removed from a sample of liquid silver at its melting point to turn it into a solid. How much silver was present in the sample? ($L_{\text{silver fusion}} = 0.88 \times 10^5\,\text{J kg}^{-1}$)

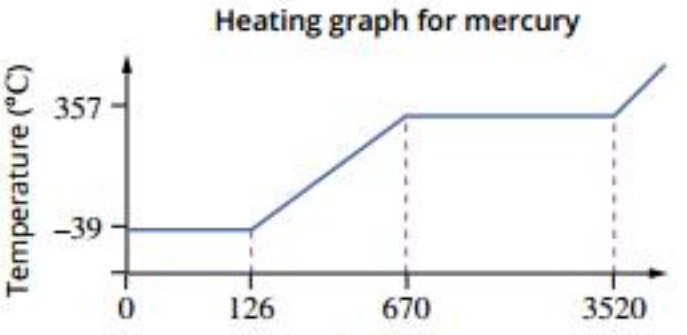
Analyse

7 How much energy is needed to boil 1.20kg of ethanol from a starting temperature of 60°C? Assume no loss of energy to the surroundings and that the ethanol completely changes state to a gas. ($c_{\text{ethanol}} = 2460\,\text{J kg}^{-1}\,\text{K}^{-1}$, $L_{\text{ethanol vapour}} = 8.7 \times 10^5\,\text{J kg}^{-1}$)

8 Determine how many kJ of energy are required to melt exactly 100.0g of ice initially at –4.00°C. Assume no loss of energy to surroundings and that the ice undergoes a full phase change. ($c_{\text{ice}} = 2100\,\text{J kg}^{-1}\text{K}^{-1}$, $L_{\text{water fusion}} = 3.34 \times 10^5\,\text{J kg}^{-1}$)

9 2.134×10^6J of energy was used to boil 9.7kg of a substance. Calculate the specific latent heat of vaporisation of the substance, then identify the substance using information contained in Table 2.5.2.

10 The graph below represents the heating curve for mercury, a metal that is a liquid at normal room temperature. Thermal energy is added to 10.0g of solid mercury, initially at a temperature of –39°C, until all of the mercury has evaporated.



a Explain why the temperature remains constant during the first part of the graph.

b Identify the melting point of mercury, in degrees Celsius.

c Identify the boiling point of mercury, in degrees Celsius.

d Determine the specific latent heat of fusion of mercury.

e Determine the specific latent heat of vaporisation of mercury.

11 Draw a heating curve for 300g of ethanol initially at −273°C. Use Tables 2.5.1 and 2.5.2, as well as the specific heat capacities of solid ethanol ($970\,\text{J kg}^{-1}\,\text{K}^{-1}$), liquid ethanol ($2460\,\text{J kg}^{-1}\,\text{K}^{-1}$) and gaseous ethanol ($1900\,\text{J kg}^{-1}\,\text{K}^{-1}$).
Note that the melting point of ethanol is −114°C and its boiling point is 78°C.

2.6 Calorimetry

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand how heat flows from a hot object to a cold object
- understand thermal equilibrium
- understand the conservation of energy with regard to thermal processes
- solve problems involving specific heat capacity, specific latent heat and thermal equilibrium.

THERMAL EQUILIBRIUM

If you leave a hot cup of coffee on a table, it will cool down until it reaches room temperature. This is because particles in the coffee will 'lose' kinetic energy to the environment until the average kinetic energy of particles in the coffee is the same as that of the environment. Similarly, if you put ice into a warm drink, it will quickly melt to leave the entire drink a little cooler than before the ice was added.

If two objects are in **thermal contact**, energy can flow between them. For example, if an ice cube is placed in a copper pan, the ice molecules are in thermal contact with the copper atoms. Assuming that the copper is warmer than the ice, thermal energy will flow from the copper to the ice. When two objects in thermal contact stop having a flow of energy between them, they are in **thermal equilibrium**. If a frozen piece of steak is placed in a container of warm water, kinetic energy is transferred from the water to the steak. The particles within the steak gain kinetic energy and the steak warms up. The water loses energy and cools down. Eventually the transfer of energy between the steak and water will stop when their particles have the same average kinetic energy. They are now in thermal equilibrium, and the steak and water will be at the same temperature.

At the point of thermal equilibrium, the temperature of the two objects will be the same. The average kinetic energy of the two objects will also be the same because average kinetic energy is a measure of temperature, as shown in Module 2.2. The flow of thermal energy when two objects are in thermal contact is due to a transfer of kinetic energy as molecules collide.

ZEROTH LAW OF THERMODYNAMICS

The topic of thermal physics involves phenomena associated with energy transfer between objects at different temperatures. Since the 19th century, scientists have developed four laws for this subject. The first two will be studied in this chapter.

The first, second and third laws had been known and understood for some time. Then another law was also determined. This final law was so important that it was decided to place it first and so it is called the zeroth law of **thermodynamics**.

The zeroth law of thermodynamics relates to thermal equilibrium and thermal contact and allows temperature to be defined. Objects in thermal contact with each other will tend towards thermal equilibrium. So, if a thermometer is placed in a glass of water, the thermometer and the water will tend towards thermal equilibrium with each other, allowing the thermometer to measure the temperature of the water. If cordial is added to the glass of water, the water and cordial will come to a thermal equilibrium. The thermometer will also reach a thermal equilibrium with the water and cordial mixture. By this point, the particles within each substance have the same average kinetic energy.

The zeroth law of thermodynamics:
If objects A and B are each in thermal equilibrium with object C, then objects A and B are in thermal equilibrium with each other.

Heat lost by one substance = heat gained by the other substance

$$Q_{lost} = Q_{gained}$$

FIGURE 2.6.1 A scientist uses a bomb calorimeter to measure a temperature change to determine the thermal energy transfer.

FIGURE 2.6.2 The Styrofoam cup is a makeshift calorimeter that insulates the process and the thermometer measures the temperature change. The beaker provides stability.

Conservation of energy

In physics, quantities that are conserved are very important. Energy is one of these conserved quantities. Energy cannot be created or destroyed; it simply changes form. In a closed system—a system from which no thermal energy can escape—if two objects are in thermal contact, the thermal energy lost by one object is the thermal energy gained by the other object; that is, $Q_{lost} = Q_{gained}$.

Calorimetry is the activity of measuring an amount of thermal energy. Calorimetry determines the specific heat capacities and specific latent heats of different substances because of the conservation of energy. To provide a closed system, scientists use insulated instruments called calorimeters to measure amounts of heat (Figure 2.6.1). Calorimeters can be used to measure the energy produced in a chemical reaction or temperature change when two different objects (at different temperatures) are combined. In a high school laboratory, a foam cup can be used to simulate the insulating environment of a calorimeter (Figure 2.6.2). This set-up could be used to determine the specific heat capacity of an unknown metal. The metal can be heated to a known temperature and then added to some water. The metal and water are allowed to come to equilibrium and the temperature increase of the water will allow the calculation of the specific heat capacity of the metal, as shown in Worked example 2.6.1.

Worked example 2.6.1

DETERMINING SPECIFIC HEAT CAPACITY USING CALORIMETRY

A 20.0 g piece of metal is heated to 100.0°C and then placed in a foam cup containing 50.0 mL of water at 24.0°C. The final temperature of the water and metal cube is 27.0°C. Calculate the specific heat capacity of the metal.

Thinking	Working
Calculate the mass of water involved. 1 L of water = 1 kg	50.0 mL of water = 0.050 kg
Find the specific heat capacity of water from Table 2.4.1 on page 21.	$c = 4200\,J\,kg^{-1}\,K^{-1}$
Use the equation $Q = mc\Delta T$ to calculate the heat energy required to change the temperature of water from 24°C to 27°C.	$Q_{water} = mc\Delta T$ $= 0.05 \times 4200 \times (27 - 24)$ $= 630\,J$
Recall that, due to conservation of energy, the heat gain by the water will be the heat lost by the metal.	$Q_{metal} = 630\,J$
Convert the mass of the metal to kilograms.	20.0 g of metal = 0.020 kg
Rearrange $Q_{metal} = mc\Delta T$ to make c the subject.	$Q_{metal} = mc\Delta T$ $c = \frac{Q_{metal}}{m\Delta T}$
Substitute in the values and find the specific heat capacity for a temperature change from 100.0°C to 27.0°C.	$c = \frac{Q_{metal}}{m\Delta T}$ $= \frac{630}{0.02 \times (100 - 27)}$ $= 430\,J\,kg^{-1}\,K^{-1}$

➤ Try yourself 2.6.1

DETERMINING SPECIFIC HEAT CAPACITY USING CALORIMETRY

A 34.6 g piece of metal has been heated to 97.0°C. This is then placed in a Styrofoam cup containing 71 mL of water at 20.0°C. The final temperature of the water and metal cube is 29.5°C. Calculate the specific heat capacity of the metal.

Worked example 2.6.2

DETERMINING FINAL TEMPERATURE OF A MIXTURE USING CALORIMETRY

Four ice cubes (20 g each) at 0.0°C were added to 250 g of water at 30°C. What is the final temperature of the drink?

Thinking	Working
Calculate the mass of the ice and water involved. 1000 g = 1 kg	4 × 20 g ice = 0.08 kg 250 g water = 0.250 kg
Find the specific latent heat of fusion for water from Table 2.5.1 on page 25.	$L_{fusion} = 3.34 \times 10^5\,J\,kg^{-1}$
Find the specific heat capacity of water from Table 2.4.1 on page 21.	$c = 4200\,J\,kg^{-1}K^{-1}$
Recall that, due to the conservation of energy, the heat gained by the ice will be the heat lost by the water.	$Q_{ice} = Q_{water}$ $m_{ice}L_{fusion} + m_{ice}c_{water}\Delta T_{water} = m_{water}c_{water}\Delta T_{water}$ $m_{ice}L_{fusion} + m_{ice}c_{water}(T_{final} - 0) = m_{water}c_{water}(30 - T_{final})$
Rearrange so that all the T_{final} terms are on the left-hand side of the equation.	$m_{ice}L_{fusion} + m_{ice}c_{water}T_{final} - 0 = 30m_{water}c_{water} - m_{water}c_{water}T_{final}$ $m_{ice}c_{water}T_{final} + m_{water}c_{water}T_{final} = -m_{ice}L_{fusion} + 30m_{water}c_{water}$ $T_{final}(m_{ice}c_{water} + m_{water}c_{water}) = -m_{ice}L_{fusion} + 30m_{water}c_{water}$
Substitute in values and find T_{final}.	$T_{final}(m_{ice}c_{water} + m_{water}c_{water}) = -m_{ice}L_{fusion} + 30m_{water}c_{water}$ $T_{final}(0.08 \times 4200 + 0.250 \times 4200) = -0.08 \times (3.34 \times 10^5) + 30 \times 0.250 \times 4200$ $T_{final} \times 1386 = 4780$ $T_{final} = 3.4°C$

➤ Try yourself 2.6.2

DETERMINING FINAL TEMPERATURE OF A MIXTURE USING CALORIMETRY

Three ice cubes (15 g each) at 0.0°C were added to 200 g of water at 20°C. What is the final temperature of the drink?

2.6 Review

SUMMARY

- If two objects are in thermal contact, thermal energy will flow from the hot object to the cold object until the two objects are at the same temperature. This is known as thermal equilibrium.
- The zeroth law of thermodynamics states that if objects A and B are each in thermal equilibrium with object C, then objects A and B are in thermal equilibrium with each other. A, B and C must be at the same temperature.
- Conservation of energy states that heat cannot be created or destroyed. This means that the thermal energy lost by one substance is gained by another.
- Calorimetry is the measurement of heat. It can be used to determine the specific heat capacity or specific latent heat of a substance.

KEY QUESTIONS

Describe

1 Describe 'calorimetry'.

2 Describe 'thermal equilibrium'.

3 Describe the average kinetic energy of two objects in thermal equilibrium.

Apply

4 Explain why two objects that are in thermal equilibrium with a third object must also be in thermal equilibrium with each other.

5 Explain why putting ice (at 0°C) into a drink is much more effective at cooling your drink down than putting water at 0°C into your drink.

6 What is the difference between adding 50 g of solid ice to a glass of water compared with adding 50 g of crushed ice to a glass of water? In your response, refer to how fast the water cools down and to the final temperature.

Analyse

7 250 mL of water at 30°C is mixed with 1 L of water at 80°C. What is the final temperature of the water?

8 A 1.4 kg piece of metal has been heated to 60.0°C. This is then placed in an insulated tank containing 18.3 kg of water at 29.0°C. The final temperature of the water and metal cube is 29.5°C. Determine the specific heat capacity of the metal and from this deduce what metal you think it is. (c_{water} = 4200 J kg^{-1} K^{-1})

9 A 5.00 kg block of iron at 60.0°C is brought in contact with a 10.0 kg block of aluminium at 30.0°C. Assume no energy is lost to the surroundings. What is the final temperature when the metals reach thermal equilibrium? (c_{iron} = 440 J kg^{-1} K^{-1}, $c_{aluminium}$ = 900 J kg^{-1} K^{-1}).

10 An unknown amount of copper at 78.0°C was added to 2.30 kg of methylated spirits at 21.0°C. The final temperature of the mixture was 25.2°C. Calculate the mass of the copper. (c_{copper} = 390 J kg^{-1} K^{-1}, $c_{methylated\ spirit}$ = 2500 J kg^{-1} K^{-1}).

2.7 Mechanical work and efficiency

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that thermal energy has the capacity to do mechanical work
- understand the conservation of energy and the first law of thermodynamics
- understand efficiency and the loss of useful energy while total energy is conserved
- calculate the efficiency of an energy transfer.

WORK

In the mid-1800s, James Joule, a British brewer, performed a series of experiments that showed the equivalence of heat and mechanical energy (Figure 2.7.1). In his heat equivalency experiment, a mass was dropped, transferring potential energy to kinetic energy (due to the conservation of energy). This dropping mass pulled a cord turning a spindle. The spindle turned some paddles, which heated the liquid, and the temperature change was measured. The kinetic energy of the turning paddles caused the surrounding liquid to increase in temperature. Through this experiment, Joule measured the heat capacity of water with a surprising level of accuracy for the time.

Work is done when energy is transferred and causes an object to move. In Joule's experiment, the turning paddle did work on the liquid, increasing the average kinetic energy of the molecules, thus increasing the temperature of the water. Joule's experiment converted potential energy and then kinetic energy from the falling mass to kinetic energy of the spindle and paddles, and then to thermal energy that heated the liquid.

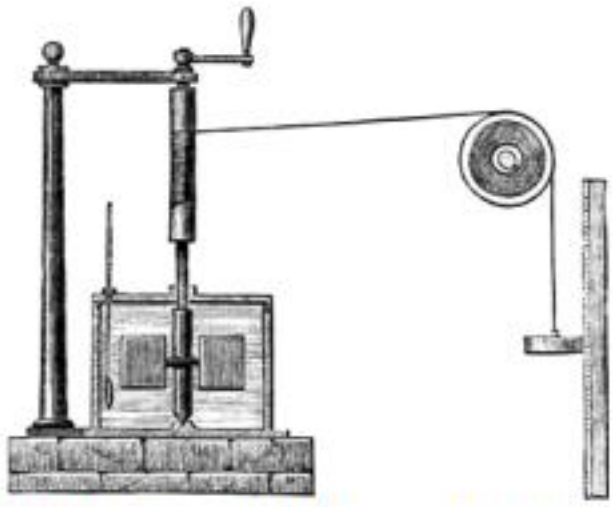


FIGURE 2.7.1 Apparatus used by James Joule to show the equivalence of heat and mechanical energy

Any system with thermal energy has the capacity to do mechanical work. For example, heat is created by the chemical reactions in an engine. The heat expands a gas, which moves a piston and work is done.

THE FIRST LAW OF THERMODYNAMICS

In a closed system, energy is always conserved. Energy cannot be created or destroyed; it can only be transferred or transformed. The first law of thermodynamics states that energy transfers from one form to another and the total internal energy in a system is constant. The internal energy of the system can be changed by heating or cooling, or by work being done on or by the system.

Any change in the internal energy, ΔU, of a system is equal to the energy added by heating, $+Q$, or removed by cooling, $-Q$, plus the work done on, $+W$, or work done by, $-W$, the system. Note that due to the conservation of energy, all energy must be accounted for in the internal energy; there is no 'lost' energy in the system.

$$\Delta U = Q + W$$

The internal energy, U, of a system is defined as the total kinetic and potential energy of the system. As the average kinetic energy of a system is related to its temperature and the potential energy of the system is related to the state, then a change in the internal energy of a system means that either the temperature changes or the state changes.

- If heat, Q, is added to the system, then the internal energy, U, rises by either increasing the temperature or changing state from solid to liquid or liquid to gas. Similarly, if work, W, is done on a system, then the internal energy rises and the system will once again increase in temperature or change state by melting or boiling. When heat is added to a system or work is done on a system, ΔU is positive.
- If heat, Q, is removed from the system, then the internal energy, U, decreases by either decreasing temperature or changing state from liquid to solid or gas to liquid. Similarly, if work, W, is done by the system, then the internal energy decreases and the system will once again decrease in temperature or change state by condensing or solidifying. When heat is removed from a system or work is done by a system, ΔU is negative.

Any change in the internal energy, ΔU, of a system is equal to the energy added by heating, $+Q$, or removed by cooling, $-Q$, plus the work done on, $+W$, or work done by, $-W$, the system.

- If heat is added to the system and work is done by the system, then the magnitude of the energy into the system compared to the magnitude of the energy out of the system determines whether the internal energy increases (ΔU is positive) or decreases (ΔU is negative).

Worked example 2.7.1

CALCULATING THE CHANGE IN INTERNAL ENERGY

A 1 L beaker of water has 25 kJ of work done on it and loses 30 kJ of thermal energy to the surroundings. Calculate the change in energy of the water.

Thinking	Working
Heat is removed from the system, so Q is negative. Work is done on the system, so W is positive.	$\Delta U = Q + W$ $= -30 + (+25)$
Note that the units are kJ, so express the final answer in kJ.	$\Delta U = -5$ kJ

➤ Try yourself 2.7.1

CALCULATING THE CHANGE IN INTERNAL ENERGY

A student places a heating element and a paddle-wheel apparatus in an insulated container of water. She calculates that the heater transfers 2530 J of thermal energy to the water and the paddle does 240 J of work on the water. Calculate the change in internal energy of the water.

EFFICIENCY

Energy can never be created or destroyed; however, it may transform into less useful forms of energy. In any heat transfer in the real world, some of the heat is 'wasted' to the surroundings. This wasted heat reduces the useable energy. The percentage of energy that is effectively transformed in an energy transfer process is called its efficiency. For example, an incandescent light bulb is only 10% energy efficient; that is, 10% of the energy output is light and 90% is wasted as heat. In comparison, a LED bulb is 90% energy efficient. There is now much more effort going into designing energy-efficient buildings and devices than in the past.

The efficiency of transferring energy from one form to another is expressed as:

$$\text{efficiency } (\eta) = \frac{\text{useful energy transferred}}{\text{total energy}} \times 100\%$$

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times 100\%$$

ℹ $\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$

Worked example 2.7.2

CALCULATING EFFICIENCY

A particular Bunsen burner provides 76 000 J of heat to a beaker of water. The useful energy that heated the water is 27 000 J. The rest of the heat is lost to the environment. Calculate the efficiency of this process.

Thinking	Working
Recall the equation for efficiency. Substitute the given values into the equation and calculate η.	energy output = 27 000 J energy input = 76 000 J $\eta = \frac{\text{energy output}}{\text{energy input}} \times 100\%$ $= \frac{27000}{76000} \times 100\%$ $= 36\%$

➤ Try yourself 2.7.2

CALCULATING EFFICIENCY

A particular barbeque produces 295 000 J of energy but the heat absorbed by the food is just 81 000 J. Determine the efficiency of this process.

2.7 Review

SUMMARY

- Thermal energy has the capacity to do mechanical work.
- The first law of thermodynamics states that energy simply changes from one form to another and the total energy in a system is constant.
- Any change in the internal energy (ΔU) of a system is equal to the energy added by heating ($+Q$) or removed by cooling ($-Q$), plus the work done on ($+W$) or by ($-W$) the system: $\Delta U = Q + W$.
- The efficiency, η, of an energy transfer from one form to another is given by:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times 100\%$$

KEY QUESTIONS

Describe

1 Describe 'conservation of energy'.

2 Explain whether it is possible to have greater than 100% efficiency in a thermal energy transfer.

3 Considering conservation of energy, would beating eggs increase or decrease their temperature?

Apply

4 Calculate the efficiency of a power station that transforms 1.4×10^7 J of heat energy into 5.0 MJ of electrical energy.

5 Calculate the efficiency of a hair dryer with an input energy of 480 kJ and a useful output energy of 326 kJ.

6 New household solar panels have an efficiency of 22%. If 82 MJ of solar energy is shining on the solar panel in a day:

a how much electrical energy is being produced?

b how much energy is being wasted?

7 Electric cars have an efficiency of power to the wheels of 77%. Petrol cars have an efficiency of power to the wheels of 25%. If a car needs 19 kJ per second to drive, calculate:

a how much input energy the electric car requires.

b how much input energy the petrol car requires.

Analyse

8 What is the efficiency of a kettle when an input energy of 584 kJ is used to heat 1.20 kg of water to raise its temperature from 23.0°C to 100°C? ($c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$)

9 A chef vigorously stirs a pot of cold water and does 150 J of work on the water. The water also gains 75 J of thermal energy from the surroundings. Calculate the change in energy of the water.

10 A scientist very carefully does mechanical work on a container of liquid sodium. The liquid sodium loses 300.0 J of energy to its surroundings but gains 250.0 J of energy overall. Calculate how much work the scientist did.

Chapter review

02

KEY TERMS

absolute zero
absorption
calorimetry
conduction
conductor
convection
electromagnetic spectrum
emission
evaporation
frequency
heat
incident
insulator
internal energy
kelvin
kinetic energy
kinetic particle model
model
Maxwell–Boltzmann distribution
potential energy
radiation
specific heat capacity
specific latent heat
specific latent heat of fusion
specific latent heat of vaporisation
temperature
thermal contact
thermal energy
thermal equilibrium
thermodynamics
volatile
wavelength
work

KEY QUESTIONS

Describe

1 Identify which of the following statements can be said to describe particles of matter, according to the kinetic particle model.

A They are in constant motion at any temperature.
B They are stationary at all temperatures.
C They are in motion above a certain temperature.
D None of these

2 Which of the following will affect the rate at which an object radiates thermal energy?

A its temperature
B its colour
C its surface nature (shiny or dull)
D all of A–C

3 Identify the units for specific heat capacity.

A $Jkg K^{-1}$
B J K
C mJK^{-1}
D $Jkg^{-1}K^{-1}$

4 Consider a solid at melting point undergoing a phase change to a liquid. During that phase change, what can be said of the internal energy and the potential energy of the substance?

	Internal energy	Potential energy
A	increases	increases
B	increases	remains the same
C	decreases	remains the same
D	remains the same	increases

5 State what the first law of thermodynamics says about the total internal energy of a closed system.

6 A heating curve is a graph of *heat* (*x*-axis) against *change in temperature* (*y*-axis). What does the gradient of the liquid phase of a heating curve represent?

Apply

7 **a** An uncooked chicken is placed into an oven that has been preheated to 180°C. Which of the following statements describes what happens as soon as the chicken is placed in the oven? You can choose more than one.

A Thermal energy flows from the chicken into the hot air.
B The chicken and the air in the oven are in thermal equilibrium.
C Thermal energy flows from the hot air into the chicken.
D The chicken and the air in the oven are not in thermal equilibrium.

b A chicken is inside an oven that has been preheated to 180°C. The chicken has been cooking for one hour and its temperature is also 180°C. Identify which of the following statements best describes this scenario.

A Thermal energy flows from the chicken into the hot air.
B The chicken and the air in the oven are in thermal equilibrium.
C Thermal energy flows from the hot air into the chicken.
D The chicken and the air in the oven are not in thermal equilibrium.

8 Identify which of the following temperatures cannot possibly exist. You can choose more than one.

A 1 000 000°C
B –50°C
C –50 K
D –300°C

9 Two cubes, one of silver and one of iron, have the same mass and temperature. A quantity of heat, Q, is removed from each cube. Identify which one of the following properties causes the final temperatures of the cubes to be different.

A density
B specific heat capacity
C specific latent heat of vaporisation
D volume

10 Consider two objects that are in thermal contact in a closed system. Explain the relationship between the heat lost from one object and the heat gained by the second object.

11 Explain how temperature differs from heat.

12 Convert:

a 5.0°C to kelvin
b 200.0 K to °C.

13 Explain why metals are more likely than wood to conduct heat.

14 A solid substance is heated but its temperature does not change. Explain what is occurring.

15 Calculate how many kilojoules of energy are required to melt exactly 80.0 g of silver ($L_{fusion} = 0.88 \times 10^5\,J\,kg^{-1}$).

16 What are the units of the ratio $\frac{\text{specific latent heat of vaporisation}}{\text{specific heat capacity}}$?

17 The heating curve for a solid shows how temperature (vertical axis) varies with heat (horizontal axis). The curve has slope G. Write an equation to calculate the mass of the solid based on the gradient.

18 Two 20.0 g cubes of ice (at –4.00°C) are added to a 20.0°C cup of water (250.0 g). Determine the final temperature of the cup of water. ($c_{ice} = 2100\,J\,kg^{-1}\,K^{-1}$, $c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$, $L_{fusion\ water} = 3.34 \times 10^5\,J\,kg^{-1}$)

19 Based on the kinetic particle model, if a substance has no thermal contact with its surroundings, does the temperature of the substance change over time?

Analyse

20 Three samples of a liquid are added to a foam cup: 20 mL at 45°C, 30 mL at 20°C and 10 mL at 0°C. What is the equilibrium temperature of the liquid?

A 15°C
B 20°C
C 25°C
D 30°C

21 Object A is heated from 25°C to 40°C. Object B is heated from 0°C to 15°C. What is the difference in heat energy provided to both objects?

A There is no difference.
B More heat is transferred to Object B.
C Less heat is transferred to Object B.
D The answer cannot be determined with the information provided.

22 A mass of water is in a calorimeter. A piece of metal half the mass of the water is placed in the water. The water changes temperature by 5 K while the metal has changed temperature by 70 K.

What is the ratio $\frac{\text{specific heat capacity of the water}}{\text{specific heat capacity of the metal}}$?

A 5
B 7
C 9
D 10

23 A sealed, thermally insulated container contains ice at 0°C and water at 15°C. Describe what happens to the total internal energy of the system over time.

A It increases.
B It decreases.
C It increases until the ice melts, then stays the same.
D It remains constant.

24 Explain the difference between internal energy and thermal energy.

25 A solid and a liquid are at thermal equilibrium with each other. Is the kinetic energy and/or internal energy of the solid the same as that of the liquid?

26 Explain the difference between solids, liquids and gases using the kinetic theory.

27 A body at a uniform temperature of 300.0 K and an internal energy of 6.0×10^6 J is split into two equal halves.

a Has any heat been exchanged?
b What is the temperature of each half?
c Determine the internal energy of each half.

28 Calculate how much energy, in J, is needed to raise the temperature of a 1.0 kg block of aluminium by 20.0°C. ($c_{aluminium} = 900\,J\,kg^{-1}\,K^{-1}$).

29 A 2.00 kg metal object requires 5.02×10^3 J of heat to raise its temperature from 20.0°C to 30.0°C. Determine the specific heat capacity of the metal in $J\,kg^{-1}\,K^{-1}$. Give your answer to the nearest whole number.

30 If 48 000 J of energy is given off when a 2.0 kg sample of a liquid cools by 12 K, determine the specific heat capacity of the liquid.

31 An unknown quantity of ice at 0.0°C is added to a 750g sample of water, the initial temperature of which is 15.0°C. The water cools down to its freezing point. How much ice was added? ($c_{ice} = 2100\,J\,kg^{-1}\,K^{-1}$, $c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$, $L_{fusion\ water} = 3.34 \times 10^5\,J\,kg^{-1}$).

32 Hypothermia is the cooling of the body to levels considerably lower than normal. The body's functions slow and death can result. A person may survive 12hours in air at 0°C before suffering hypothermia but may survive only a few minutes in water at 0°C. Consider why this is so and how wetsuits can help you survive in cold water.

33 You have 30.0g of ethanol at 22°C, which you pour into 90.0g of water at 80.0°C. Assuming no heat is produced or lost during this process, calculate the final temperature of the mixture. ($c_{ethanol} = 2460\,J\,kg^{-1}\,K^{-1}$, $c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$)

34 A heater that is 25% efficient receives 3000.0J of energy per second. Determine how much of this energy is put out as heat.

35 Describe a system in which thermal energy is converted into mechanical work.

Interpret

36 Create an analogy for the three main states of matter (solid, liquid and gas) to explain them to a younger student.

37 Design a cold storage room, powered by a small refrigeration unit, for keeping food fresh in a hot climate. Draw a sketch of your design, clearly showing its insulating features and materials and describe how it minimises all forms of heat transfer.

38 You have a small cube of an unknown metal that you want to identify. Your teacher has suggested that measuring its specific heat capacity would help you identify it. Design an experiment to measure the specific heat capacity of the cube.

Data analysis

DATA SET 1

The information below applies to Questions 1–6.

An experiment was conducted to determine the specific heat capacity of a metal cube and thus identify the metal. The metal cube was placed in near-boiling water to bring it up to 100°C. The metal cube was then moved to a known mass of water at room temperature in a foam cup. The temperature change of the water in the foam cup was measured. The results can be seen in Figure 1. A list of specific heat capacities of common metals is provided in Table 1.

The mass of the metal cube was 11.2 g and it had an initial temperature in the near-boiling water of 95.4°C.

The mass of the room-temperature water was 67.1 g.

The specific heat capacity of water is 4200 $J kg^{-1} K^{-1}$.

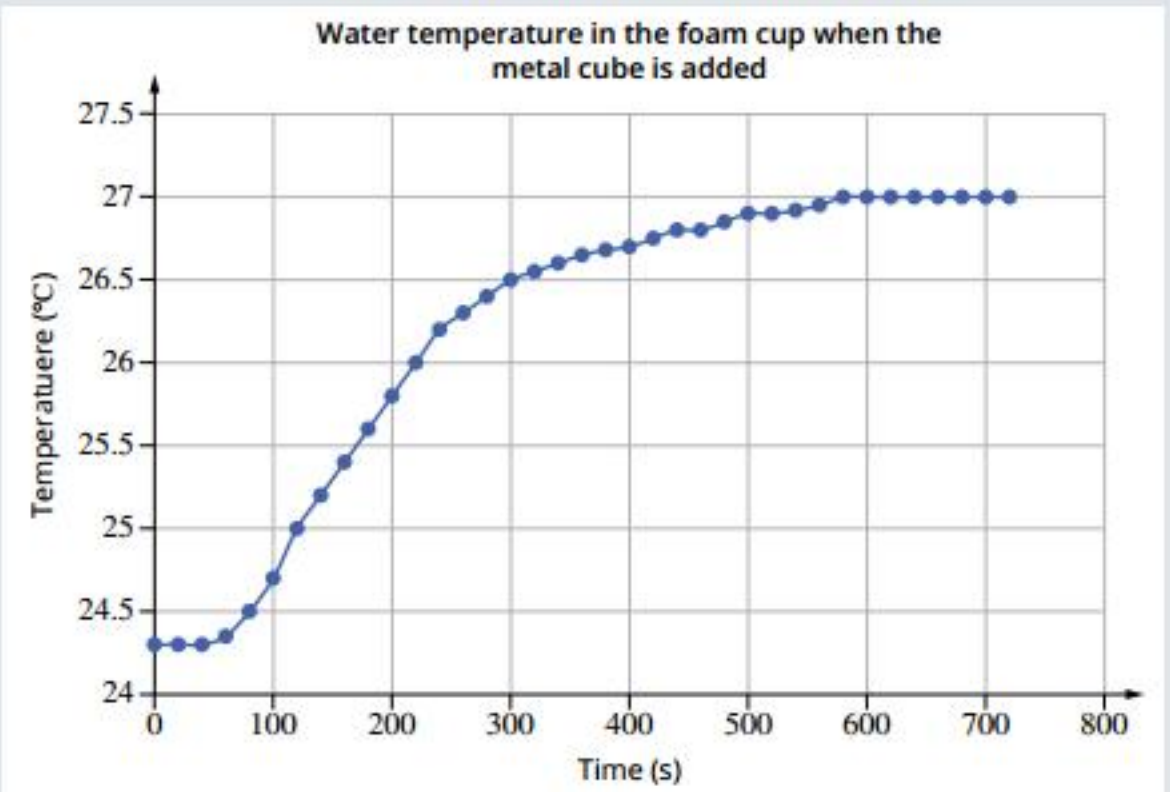


FIGURE 1 Water temperature in the foam cup when the metal cube is added

TABLE 1 Specific heat capacities of common metals

Metal	c ($J kg^{-1} K^{-1}$)
lead	130
brass	370
copper	390
iron	440
stainless steel	510
aluminium	900

Question 1 (1 mark)

Identify the final temperature of the water in the foam cup.

Question 2 (1 mark)

Calculate the temperature difference experienced by the metal cube.

Question 3 (4 marks)

Determine the specific heat capacity of the metal.

Question 4 (1 mark)

Identify the metal.

Question 5 (2 marks)

If a small amount of near-boiling water was mistakenly added along with the metal cube to the room temperature water, predict what effect this would have on the specific heat capacity calculated.

Question 6 (2 marks)

If heat is transferred into the room through the foam cup, determine what effect this would have on the calculated specific heat capacity. Explain why this would not be considered a large uncertainty for this experiment.

CHAPTER

03 Ionising radiation and nuclear reactions

This chapter examines the nature and properties of the nucleus of an atom, including the natural causes of nuclear instability and alpha, beta and gamma radiation. It also explains the importance of the rate of decay and the penetrating power of the radiation. The half-lives of radioactive substances are analysed using mathematical calculations and graphs. Finally, the energy released during nuclear fission and nuclear fusion reactions are calculated using Einstein's mass–energy relationship.

Syllabus subject matter

NUCLEAR MODEL AND STABILITY

- Describe the nuclear model of the atom characterised by a small nucleus surrounded by electrons. **3.1**
- Describe nuclides using ${}^{A}_{Z}X$ nomenclature. **3.1**
- Explain why protons in the nucleus repel each other. **3.2**
- Describe the concept of the strong nuclear force. **3.2**
- Explain the stability of a nuclide in terms of the operation of the strong nuclear force over very short distances, electrostatic repulsion, and the relative number of protons and neutrons in the nucleus. **3.2**
- Explain natural radioactive decay in terms of stability. **3.3**
- Describe alpha, beta positive, beta negative and gamma radiation, including the properties of penetrating ability, charge, mass and ionisation ability. **3.3**
- Explain how an excess of mass, protons or neutrons in a nucleus can result in alpha, beta positive and beta negative decay. **3.3**
- Solve problems involving balancing nuclear equations. **3.3**
- Describe spontaneous alpha, beta positive and beta negative decay using decay equations. **3.3**
- Explain how a radionuclide will, through a series of spontaneous decays, become a stable nuclide. **3.3**
- Describe the concept of half-life. **3.4**
- Solve radioactive decay problems using $N = N_0\left(\frac{1}{2}\right)^n$ and other arithmetic or graphical methods. **3.4**

ENERGY AND MASS DEFECT

- Describe energy in terms of electron volts (eV) and joules (J). **3.5**
- Describe the concept of artificial transmutation. **3.5**
- Describe nuclear fission and nuclear fusion with the aid of nuclear equations. **3.6**
- Distinguish between artificial transmutations and natural radioactive decay. **3.5**
- Explain a neutron-induced nuclear fission reaction, including references to extra neutrons produced from many of these reactions. **3.6**
- Explain a fission chain reaction. **3.6**
- Describe the concepts of mass defect, binding energy and binding energy per nucleon. **3.5**
- Describe the mass–energy equivalence relationship. **3.5**
- Solve problems involving the mass–energy equivalence relationship using $\Delta E = \Delta m c^2$. **3.5, 3.6**
- Explain that more energy is released per nucleon in nuclear fusion than in nuclear fission because a greater percentage of the mass is transformed into energy. **3.6**

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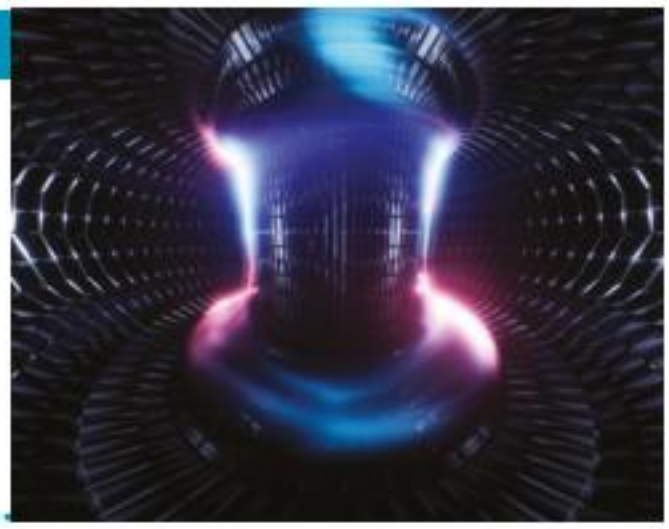
3.1 The nucleus



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the nucleus in terms of the charges and masses of its constituent nucleons
- recall that a nucleon is a proton or a neutron
- recall that isotopes of an element have the same number of protons but different numbers of neutrons
- recall that the nucleus of an isotope is called a nuclide
- use the ${}^{A}_{Z}X$ notation to calculate the number of protons and neutrons in a nuclide.

The atom is the basic building block of all matter. The first **subatomic** particle, the **electron**, was discovered by English physicist J. J. Thomson in 1897. He then refined the first testable model of the atom, called the 'plum pudding model' (Figure 3.1.1). This model described the **neutral** atom as negatively charged 'plums' of electrons embedded in a loosely packed 'pudding' of positive charge.

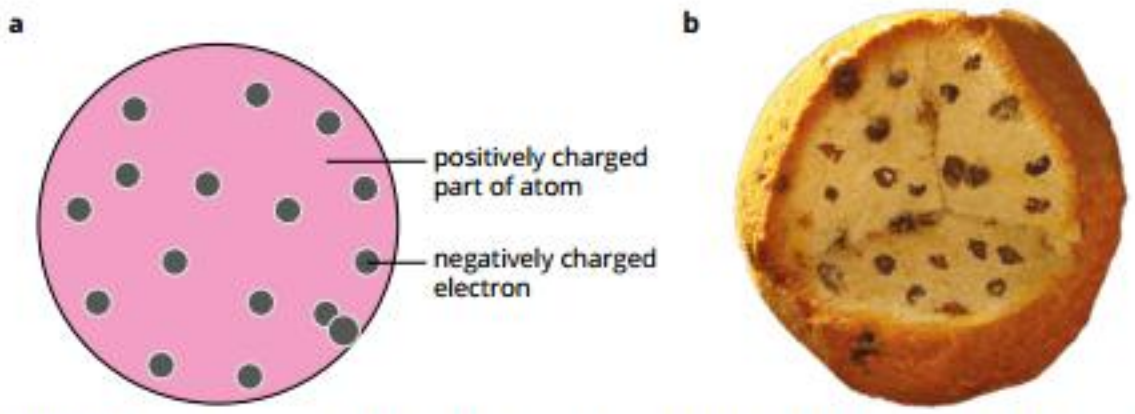


FIGURE 3.1.1 (a) The 1897 'plum pudding model' of the atom, the first truly physical model of the atom that could be tested, and (b) a real plum pudding

While the plum pudding model was only accepted for a short time, it allowed for further experimentation and analysis of the atom. In 1909, the New Zealand physicist Ernest Rutherford showed that the atom consisted of a very dense, positively charged nucleus surrounded by much smaller, negatively charged electrons.

NUCLEAR STRUCTURE

The proton

Rutherford also discovered that the nucleus of an atom is made up of individual positive charges called protons. A **proton** has a mass almost 2000 times that of the electron. The number of protons contained in a nucleus determines the species, or element, of the atom. For example, hydrogen always has one proton; helium always has two protons and so on.

The neutron

Rutherford knew that the mass of the protons in certain atoms did not add up to the mass of the nucleus. He suggested that there must be another particle contained in the nucleus that had to have no charge. The English physicist James Chadwick discovered this neutral particle, known as the neutron, in 1932. Table 3.1.1 on page 46 summarises the properties of the three major particles found in atoms. The masses are given in kg and in **unified atomic mass units** (u); charge is given in **coulombs** (C).

The nucleus of an atom consists of positively charged protons and neutral neutrons surrounded by much lighter, negatively charged electrons.

TABLE 3.1.1 A summary of the properties of the three major particles found in atoms

Particle	Location	Charge (C)	Mass (kg)	Mass (u)	Relative mass (proton = 1)
electron	surrounding nucleus	-1.602×10^{-19}	9.109384×10^{-31}	0.000549	$\frac{1}{1836}$ or 0.000545
proton	nucleus	$+1.602 \times 10^{-19}$	$1.67262171 \times 10^{-27}$	1.007276	1
neutron	nucleus	0	$1.67492729 \times 10^{-27}$	1.008665	1.0014

ISOTOPES AND NOTATION

In order to keep track of the number of particles that make up the nucleus of each atom, some notation will be introduced that describes how many protons and neutrons are in each nucleus.

Isotopes and nuclides

Nucleons is the collective name for the particles—protons and neutrons—that make up the nucleus of an atom. A **nuclide** is the specific type of nucleus formed by a particular number of protons and neutrons. An **isotope** is an atom that contains the same number of protons but a different number of neutrons. Isotopes have the same chemical properties but have different physical properties, such as density and volume, and different nuclear properties. Table 3.1.2 lists the naturally occurring isotopes of hydrogen. These isotopes are shown graphically in Figure 3.1.2.

TABLE 3.1.2 The naturally occurring isotopes of hydrogen. Note that protium is the same particle as a single proton and the ${}_{1}^{1}\mathrm{H}$ symbol is often used as the symbol for a proton.

Name of isotope	Number of protons in the nucleus	Number of neutrons in the nucleus	Number of nucleons in the nucleus	Symbol
protium	1	0	1	${}_{1}^{1}\mathrm{H}$ or ${}_{1}^{1}\mathrm{p}$
deuterium	1	1	2	${}_{1}^{2}\mathrm{H}$ or ${}_{1}^{2}\mathrm{D}$
tritium	1	2	3	${}_{1}^{3}\mathrm{H}$ or ${}_{1}^{3}\mathrm{T}$

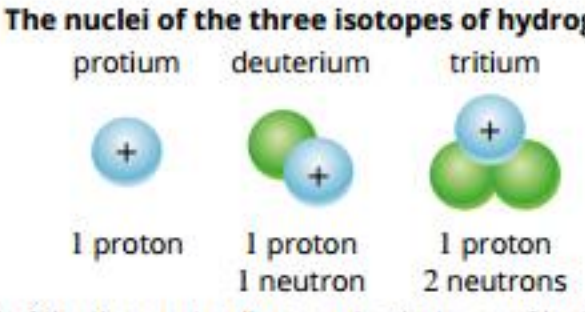


FIGURE 3.1.2 The nuclei of the three naturally occurring isotopes of hydrogen, showing the relative numbers of protons and neutrons in each case

Nuclear notation

The number of protons in a nucleus tells us the **atomic number**, Z, of the element itself. The number of neutrons in a nucleus is the **neutron number**, N. In most nuclides there are more neutrons than protons, and this ratio increases as the atomic number increases.

The sum of the number of protons and neutrons in a nucleus tells us the isotope of the element. This is the **mass number**, A.

$$A = Z + N$$

The nuclide is written using the atomic and mass numbers using the following notation, where X is the symbol for the element:

$$^{A}_{Z}X$$

Sometimes the atomic number, Z, is left out because the symbol for the element describes the atomic number (e.g. carbon C will have 6 protons), but the top number is always bigger than or equal to the bottom number.

Another way to write an isotope is to use the name of the element followed by a hyphen (-) and then the mass number of the nuclide. Examples using nuclide notation are given in Table 3.1.3. The electron and neutron are also written using nuclide notation, as they will be used again later in this chapter.

TABLE 3.1.3 Selected isotopes and nuclides and their symbols

Isotope name	Atomic number	Neutron number	Mass number	Nuclide symbol
strontium-90	38	52	90	$^{90}_{38}Sr$
carbon-12	6	6	12	$^{12}_{6}C$
carbon-14	6	8	14	$^{14}_{6}C$
plutonium-239	94	145	239	$^{239}_{94}Pu$
helium-4	2	2	4	$^{4}_{2}He$
a single electron	−1 (technically this is not the atomic number but the charge of the electron)	0	0	$^{0}_{-1}e$ or $^{0}_{-1}\beta$
a single neutron	0	1	1	$^{1}_{0}n$

Nuclides are written using notation $^{A}_{Z}X$, where Z is the number of protons, A is the number of protons plus neutrons, and X is the symbol for the element.

Isotopes are written using element notation, where the element name is followed by a hyphen and the mass number of the isotope. For example, the carbon-12 isotope has a mass number of 12 and the carbon-14 isotope has a mass number of 14.

Worked example 3.1.1

WRITING NUCLIDES

Uranium has an isotope that contains 146 neutrons. Write the nuclide of this isotope using the $^{A}_{Z}X$ notation and the element name notation.

Thinking	Working
Uranium is number 92 on the periodic table of elements (refer to Figure 3.2.2) so has an atomic number of 92.	$Z = 92$ Symbol U
The neutron number of 146 is given in the question.	$N = 146$
The mass number is the sum of the atomic number and neutron number.	$A = Z + N$ $A = 92 + 146$ $A = 238$
Write the nuclide using the $^{A}_{Z}X$ notation.	$^{238}_{92}U$ or ^{238}U
Use element name notation.	Uranium-238

➤ Try yourself 3.1.1

WRITING NUCLIDES

Consider the isotope of thorium, $^{230}_{90}Th$. Identify the number of protons, nucleons and neutrons in this isotope.

3.1 Review

SUMMARY

- The nucleus of an atom consists of positively charged protons and neutral neutrons.
- Collectively, protons and neutrons are known as nucleons.
- Negatively charged electrons surround the nucleus.
- The nucleus of the atom is extremely small but contains most of the atom's mass.
- Isotopes of an element have the same number of protons but different numbers of neutrons.
- Isotopes of an element are chemically identical to each other but have different physical properties.
- The atomic number, Z, is the number of protons in the nucleus.
- The mass number, A, is the number of nucleons in the nucleus; that is, the combined number of protons and neutrons.
- Nuclides are represented as ${}^{A}_{Z}X$.
- The nucleus of an isotope is known as a nuclide.

KEY QUESTIONS

Describe

1 Describe the 'plum pudding' model of the atom in terms of positive and negative charges.

2 State the particles that make up the nucleus of an atom and their charges.

3 State the charges of the following particles: proton, electron and neutron.

Apply

4 Explain how the number of electrons in a neutral atom is determined.

5 How many neutrons are found in the ${}^{210}_{84}Po$ nuclide?

6 How many protons and how many neutrons are there in the ${}^{197}_{79}Au$ nuclide?

7 How many nucleons are there in the ${}^{235}_{92}U$ nuclide?

8 Approximately how many times heavier is a proton than an electron?

Analyse

9 Distinguish between an isotope and a nuclide.

10 Distinguish between a nucleon and a neutron.

11 Write the nuclide for a nucleus containing 19 nucleons for an isotope of fluorine, symbol F, in ${}^{A}_{Z}X$ notation.

12 Write the nuclide for a nucleus containing 122 nucleons and 69 neutrons in ${}^{A}_{Z}X$ notation.

3.2 Stability of the nucleus

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that protons in the nucleus experience a repelling electrostatic force
- explain how the strong nuclear force acts as an attractive force on all nucleons
- explain why some nuclei are stable and some are unstable
- use a Segre plot to determine the stability of a given nuclide.

In 1896, the French physicist Henri Becquerel wrapped a metal Maltese cross in a piece of unexposed film with a chunk of uranium ore and left them in a desk drawer. On the following morning, he found that the film had become exposed and the shadow of the cross was very visible (Figure 3.2.1). The only object that could have done that was some kind of **radiation** originating from the uranium.

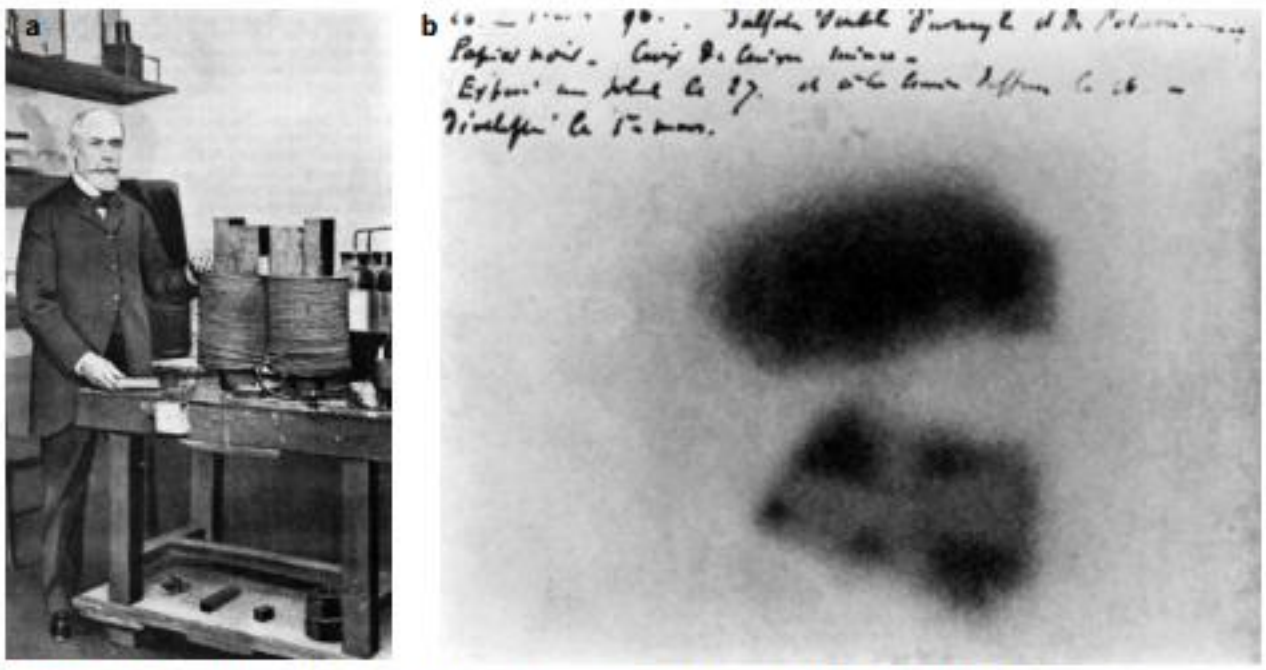


FIGURE 3.2.1 (a) Henri Becquerel in his laboratory in Paris in 1896, where he discovered radioactivity and (b) the shadow of a Maltese cross (the light grey cross) placed between a photographic plate and a uranium salt. The uranium salt emitted a strange form of radiation that exposed part of the plate (the black part surrounding the cross), leaving behind the shadow of the cross.

This phenomenon is called **radioactivity** and is the natural, spontaneous **decay** (breaking apart) of a nucleus into smaller pieces with the emission of other particles and/or energy in the form of **electromagnetic waves** (typically X-rays or gamma rays). In 1898, Marie Curie, a student of Becquerel's, discovered that thorium, radium and polonium also exhibit radioactivity.

STABLE AND UNSTABLE ISOTOPES

If a particular nuclide does not lose or gain any protons, neutrons or energy over time, then it is said to be stable. There are about 250 stable nuclides that exist in nature, with lead-208 being the heaviest naturally occurring stable nuclide. Examples of stable isotopes are carbon-12, helium-4, aluminium-27 and gold-197. In the periodic table of elements shown in Figure 3.2.2 on page 50, the elements that do not have any stable isotopes are highlighted by shading. The first 94 elements are naturally occurring.

	Group 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H 1.01																	2 He 4.00
2	3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.91	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30
6	55 Cs 132.91	56 Ba 137.34	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Ds (271)	111 Rg (272)	112 Cn (277)	113 Nh (284)	114 Fl (289)	115 Mc (288)	116 Lv (293)	117 Ts (294)	118 Og (294)

Lanthanides

58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97

Actinides

90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

Every isotope of these elements is radioactive.

FIGURE 3.2.2 This periodic table of elements highlights all elements that have no stable isotopes.

FIGURE 3.2.3 The universal symbol for a radioactive substance

FIGURE 3.2.4 The 4.8 kg plutonium-238 oxide radioisotope thermionic generator that is used by the *Curiosity* rover as a source of power on the surface of Mars. The red glow is due to the energy given off by the radioactive decay of the $^{238}_{94}Pu$ nuclei.

If the number of protons or neutrons in each nuclide changes over time, or if the nucleus has an excess of energy, then the nuclide is said to be unstable or **radioactive**, and the isotope itself is called a **radioisotope**. The unstable nucleus is known as a **radionuclide**. The universal symbol for a radioactive substance is shown in Figure 3.2.3. Sometimes the process of losing protons, neutrons or energy is enough for the leftover nuclide to become stable; at other times, the leftover nuclide may still be radioactive.

There are thousands of radioisotopes, most of which have been artificially created in **nuclear reactors** and **particle accelerators**. Figure 3.2.4 shows the red glow of the radioisotope plutonium-238 due to its own rapid decay. Many isotopes of plutonium are used as a heat source and a source of electricity to power space probes, such as in this generator on the *Curiosity* rover on the surface of Mars.

NUCLEAR FORCES

Remember that the nucleus consists of positively charged protons and neutral neutrons in very close proximity to each other. A fundamental law of physics states that charged particles have a force acting on them that causes them to move if the force is not balanced. This is known as the **coulomb force** or **electrostatic force**. The force is repulsive for two particles of the same charge, and attractive for two particles of opposite charge. Note that there is no coulomb force between two neutrons or between a neutron and a proton, because a neutron carries no charge.

Protons are all positively charged, so you would expect them to repel each other, causing the nucleus to break apart. If this was the case, there should be no elements heavier than hydrogen (with only one proton) in our universe. There are elements heavier than hydrogen in our universe, so what keeps protons from flying apart?

A large nucleus such as uranium-238 contains 92 protons, which all exert a repulsive force on each other, yet uranium exists and so the nucleus somehow stays together. Figure 3.2.5 shows the relative sizes, to scale, of the isotopes hydrogen-1 (a single proton) and uranium-238.

The coulomb or electrostatic force causes protons to repel each other.

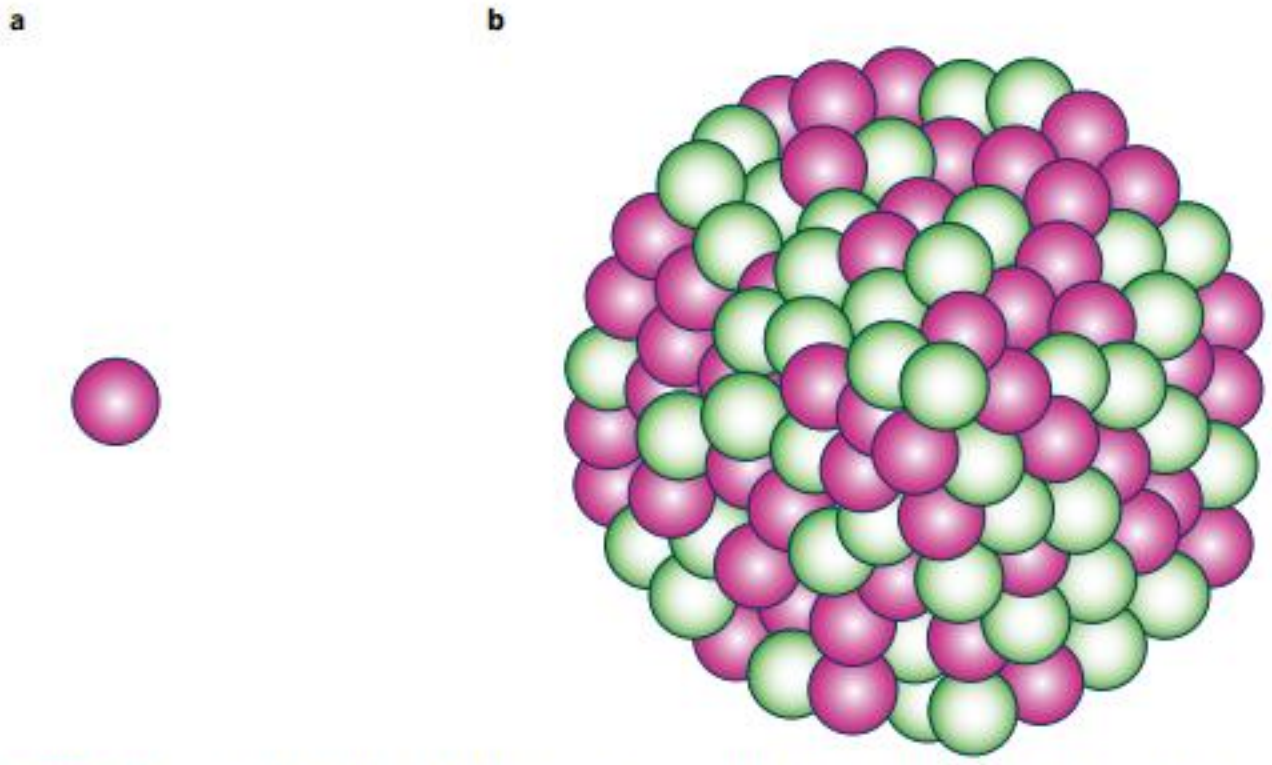


FIGURE 3.2.5 The relative sizes of (a) the hydrogen-1, and (b) the uranium-238 isotopes drawn to scale. Uranium-238 is just over eight times larger in radius than a proton.

The strong nuclear force

To overcome this apparent instability and keep the nucleus together, there must be another force operating that is larger than the repulsive force. This extra force is known as the **strong nuclear force** (SNF).

There are several important aspects of the SNF:

- It is one of the four fundamental forces that exist in the universe. The others are the electromagnetic force, gravity and the weak nuclear force.
- It is *mostly* an attractive force.
- It acts only in the nucleus on protons and neutrons.
- It acts at very short distances of up to 1 fm (10^{-15} m) on adjacent nucleons.

Think of the SNF as a piece of hoop-and-loop fastening tape (such as velcro) wrapped around the protons. Only when the protons are close enough will the tape attach and hold the protons together. If the protons are too far apart then the tape cannot stick and the protons will be forced away from each other. Figure 3.2.6 shows how the SNF holds the protons and neutrons together in a nucleus, and how the nucleus would fly apart without it.

The more protons there are in a nucleus, the larger the repulsive force. This means that the SNF must also act on neutrons to keep the nucleus from flying apart. If more protons are added to a nucleus, then more neutrons must be added for the SNF to balance the coulomb force. For some nuclides, only one more or one fewer neutrons is the difference between stability and instability.

The strong nuclear force is an attractive force that acts on very close nucleons.

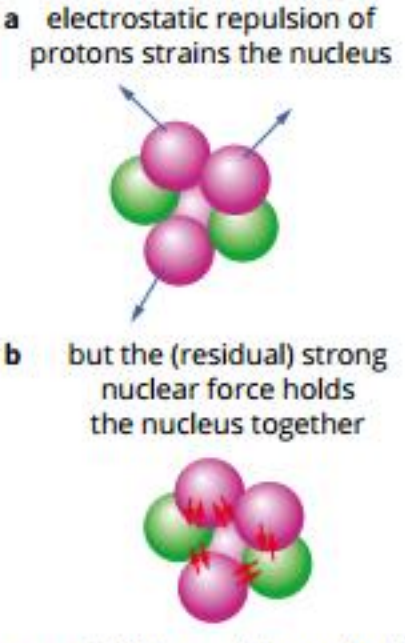

a electrostatic repulsion of protons strains the nucleus
b but the (residual) strong nuclear force holds the nucleus together

FIGURE 3.2.6 (a) The repulsive coulomb forces act on the protons (in pink) in a nucleus, tearing it apart, and (b) the SNF (shown here as red arrows) keeps the nucleus stable.

SEGRE PLOTS

A nuclide may have too many protons compared to the number of neutrons in its nucleus for it to be stable. If this is the case, then the nuclide will be unstable. For it to become stable, one proton is spontaneously turned into a neutron, with the release of energy and other particles. This is known as beta positive decay and will be discussed further in Module 3.3.

Similarly, if a nuclide has too many neutrons compared to the number of protons in its nucleus, it will also be unstable. For it to become stable, one neutron is spontaneously turned into a proton, with the release of energy and other particles. This is the reverse of the previous example and therefore it is called beta negative decay.

A graph of every isotope's neutron number, N, versus its atomic number, Z, is called a **Segre plot** (Figure 3.2.7).

A Segre plot is a graph of neutron number versus atomic number for various isotopes.

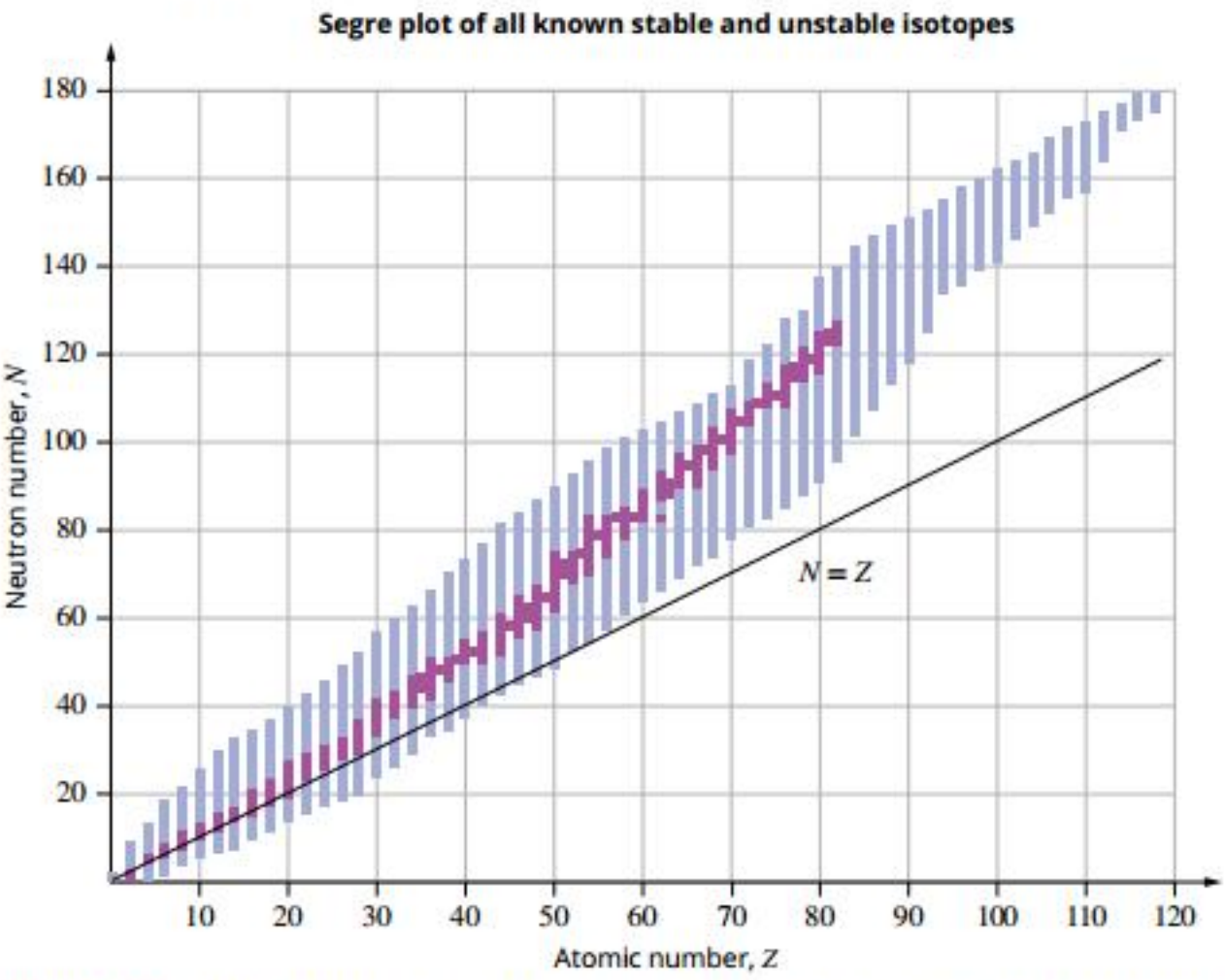


FIGURE 3.2.7 A graph of the neutron number, N, graphed against the atomic number Z, highlighting the stable nuclides (purple) and radioactive nuclides (lilac). The straight black line represents nuclides that have an equal number of protons and neutrons.

In this Segre plot, the darker, purple nuclides are stable, and the lighter, lilac nuclides are radioactive. Note that there are no stable nuclides beyond atomic number 82 (lead) and that there are no stable nuclides for atomic number 43 (technetium) or atomic number 61 (promethium). Nuclides located above any stable nuclide have too many neutrons, so they will become more stable by spontaneously losing neutrons. Nuclides below any stable nuclides have too many protons so they will lose protons to become stable.

The further away vertically from any stable nuclide, the more unstable a nuclide will be.

Notice that lighter isotopes (up to $Z = 10$) have the same number of neutrons as protons but, as the atomic number becomes greater than 10, the number of neutrons steadily becomes larger than the number of protons, up to about one-and-a-half times. This is seen in the upward trend away from the $N = Z$ line. This is because as the number of protons in a nucleus increases, the coulomb repulsive force increases, and more neutral particles are needed to balance that force so the SNF can act. There are only two stable nuclides that have more protons than neutrons ($^{1}_{1}\mathrm{H}$ and $^{3}_{2}\mathrm{He}$).

SKILLBUILDER

Using Segre plots

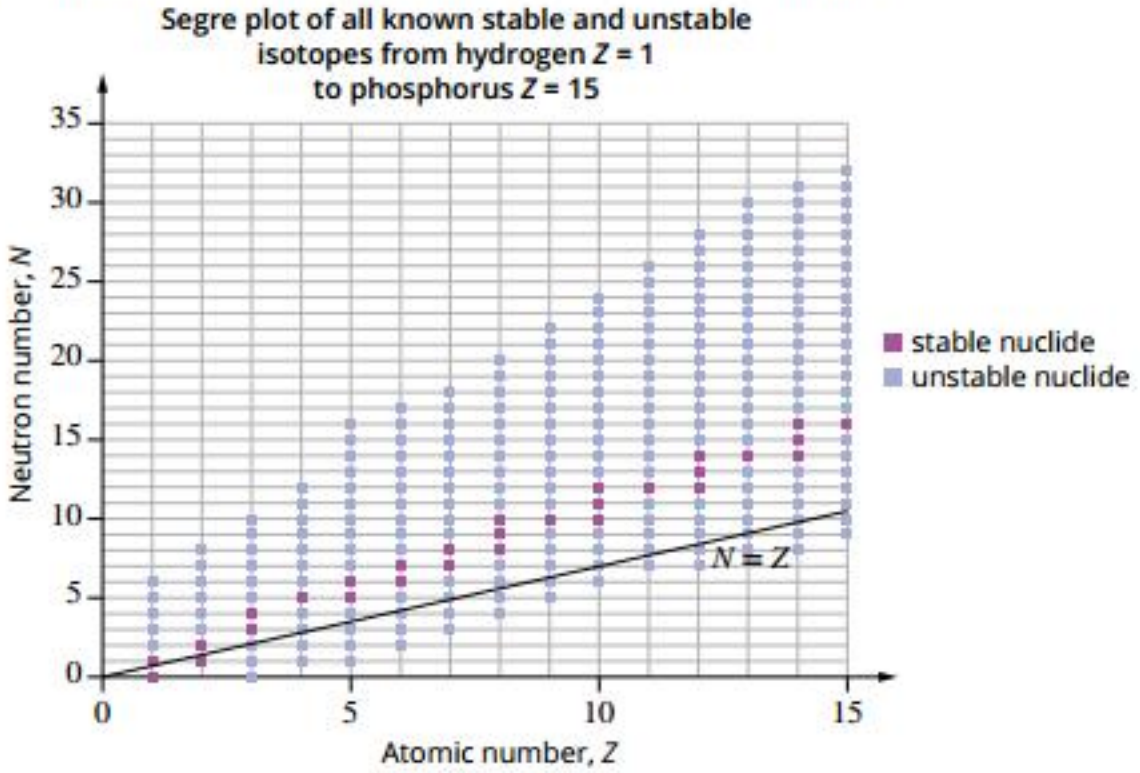
A Segre plot shows a graph of all the known nuclides when their neutron numbers (vertically) are graphed against their atomic numbers (horizontally). Different colours are used to distinguish stable nuclides and unstable nuclides. Often, a straight line is drawn on the plot, indicating the nuclides that have the same number of protons as neutrons, that is, $N = Z$.

To use a Segre plot to determine if a given nuclide is unstable or stable, you need to know its atomic number, Z, and its neutron number, N. Each nuclide is written in the ${}^{A}_{Z}\text{X}$ format, so the number of neutrons needs to be determined from the mass number, A, and atomic number, Z:

$$N = A - Z$$

Now locate the nuclide on the Segre plot by finding its atomic number horizontally, then moving vertically up to its neutron number. Finally, refer to the legend to determine if the nuclide is stable or unstable.

The Segre plot below shows all nuclides from atomic number zero to atomic number 15:



The squares in lilac indicate unstable nuclides, while the squares in purple indicate stable nuclides. The $N = Z$ line identifies any nuclides that have equal numbers of protons and neutrons.

Example

Use this Segre plot to determine if the following nuclides are stable or unstable:

a) ${}^{2}_{1}\text{H}$ **b)** ${}^{33}_{14}\text{Si}$

Solution

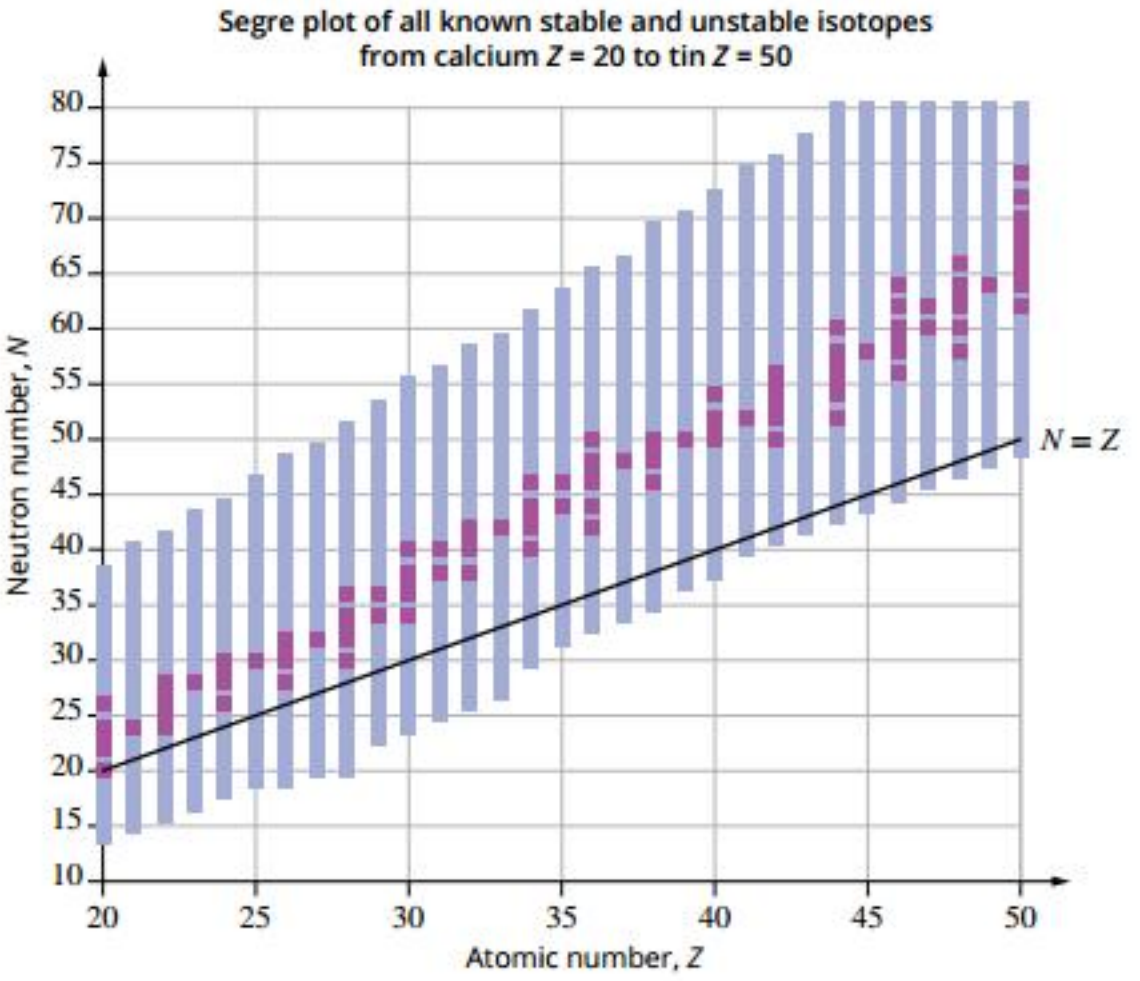
a) ${}^{2}_{1}\text{H}$ contains 1 proton ($Z = 1$) and 1 neutron ($N = 1$), so it is located at the far bottom left of the Segre plot. It is a purple-coloured square, which means ${}^{2}_{1}\text{H}$ is stable.

b) ${}^{33}_{14}\text{Si}$ contains 14 protons ($Z = 14$), and $33 - 14 = 19$ neutrons ($N = 19$). The square for an atomic number of 14 and a neutron number of 19 is lilac, so ${}^{33}_{14}\text{Si}$ is unstable.

Worked example 3.2.1

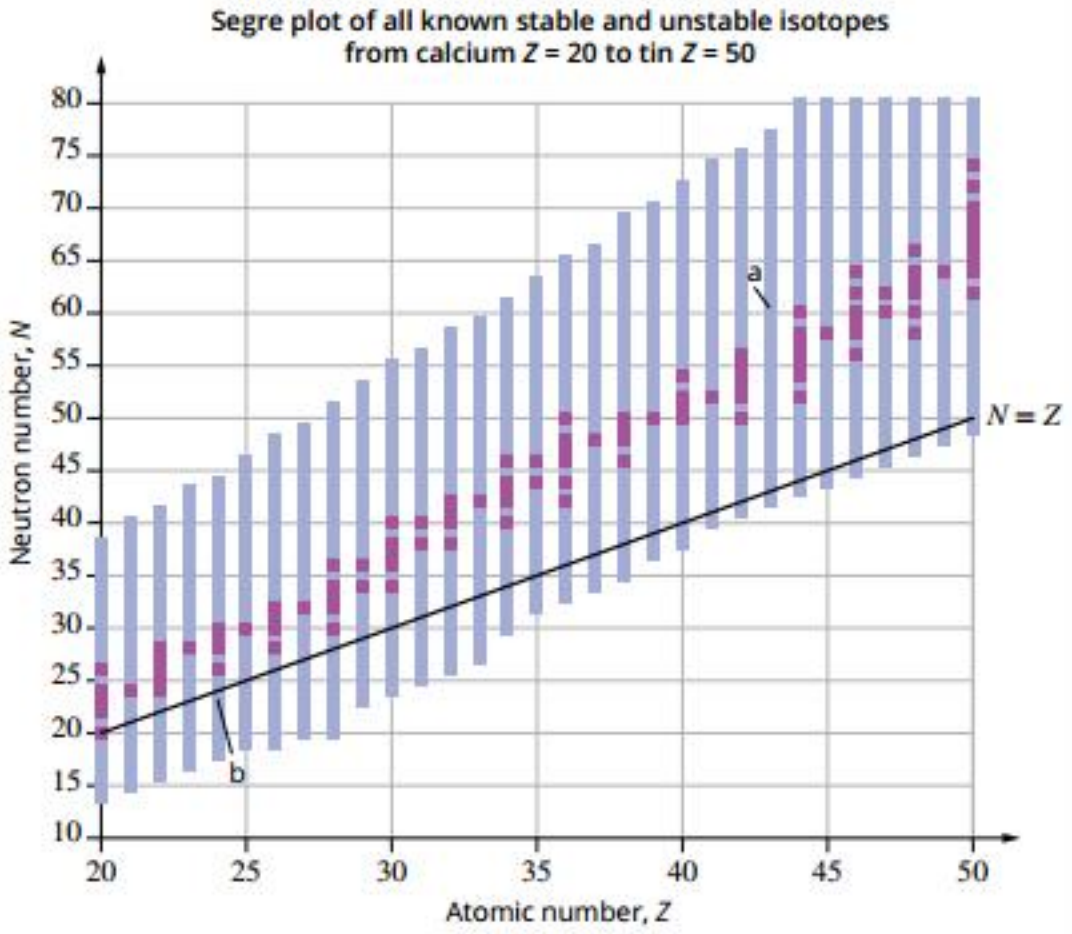
USING A SEGRE PLOT

Use the part of the Segre plot given below to identify whether each nuclide is stable or radioactive. Predict how the nuclide will become more stable if it is radioactive.



a $^{103}_{43}\text{Tc}$

Thinking	Working
First, find each nuclide on the Segre plot and note its colour. Use the nuclide's notation to obtain the neutron number, N, and atomic number, Z. Remember that the bottom number is Z and the top number is the mass number, which is the atomic number plus the neutron number. Therefore, the neutron number will be the top number minus the bottom number.	$Z = 43$ $N = 103 - 43 = 60$

Now that Z and N are known, locate them on the Segre plot. Remember that Z is the horizontal axis and N is the vertical axis. Highlight these values on the graph.	
If a nuclide is above the main purple line of stable nuclides, it has too many neutrons to be stable, so it will turn a neutron into a proton (it will lose a neutron).	$^{103}_{43}$Tc is radioactive and will try to become stable by turning a neutron into a proton.

b $^{47}_{24}$Cr

Thinking	Working
First, find the nuclide on the Segre plot and note its colour. Use the nuclide's notation to obtain the neutron number, N, and atomic number, Z. Remember that the bottom number is Z and the top number is the mass number, which is the atomic number plus the neutron number. Locate Z and N on the Segre plot above. Remember that Z is the horizontal axis and N is the vertical axis.	$Z = 24$ $N = 47 - 24 = 23$
If a nuclide is below the main purple line, it has too many protons to be stable, so it will turn a proton into a neutron (it will lose a proton).	$^{47}_{24}$Cr is radioactive and will try to become stable by turning a proton into a neutron.

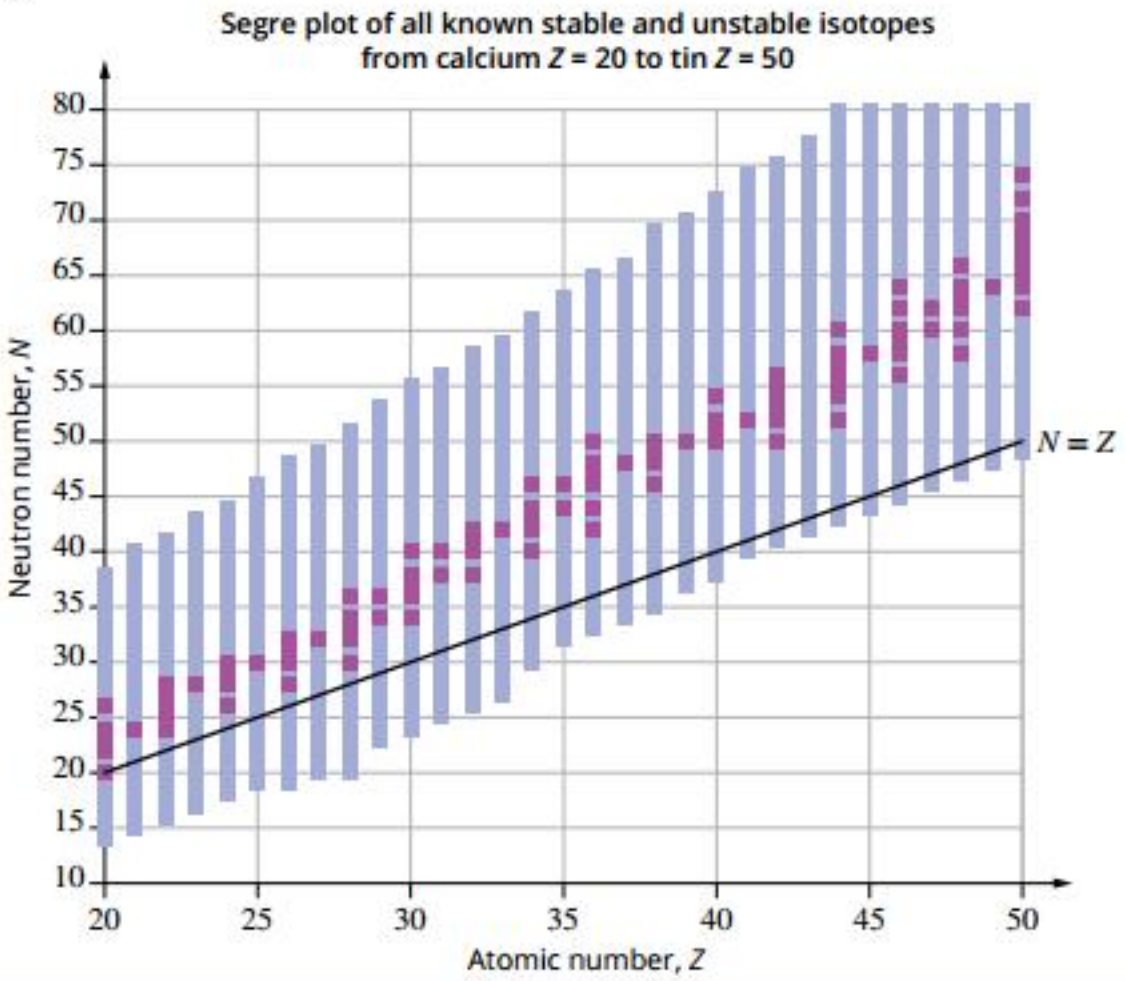
➤ Try yourself 3.2.1

USING A SEGRE PLOT

Use the part of the Segre plot given below to identify whether each nuclide is stable or radioactive. Predict how the nuclide will become more stable if it is radioactive.

a $^{108}_{48}Cd$

b $^{80}_{30}Zn$



3.2 Review

SUMMARY

- In a nucleus, protons repel each other due to the coulomb, or electrostatic force.
- The strong nuclear force keeps the nucleus together by acting as an attractive force on all nucleons.
- The strong nuclear force only acts over very short distances, in the order of 10^{-15} m.
- The radius of a nucleus increases with atomic number.
- The relative number of neutrons compared to the number of protons increases as the atomic number increases.
- A Segre plot shows all stable and radioactive nuclides known.
- A Segre plot is used to determine if a nuclide is stable and, if not, how it will become more stable.

KEY QUESTIONS

Describe

1 Describe the force that causes protons to repel.

2 State whether a natural isotope can be radioactive. If so, list two examples of such an isotope.

3 State whether a synthetic (human-made) isotope can be stable. If so, give an example of one of these isotopes.

4 State the range of the strong nuclear force.

Apply

5 Describe how the strong nuclear force tries to keep the nucleus together.

6 Describe how the electrostatic force tries to rip nuclei apart.

7 $^{4}_{2}$He is a very stable nuclide and contains two protons and two neutrons. $^{197}_{79}$Au is also a very stable nuclide yet it contains many more neutrons than protons in its nucleus. Explain why both nuclides can be stable even though they have very different ratios of protons to neutrons in their nuclei.

8 Explain why isotopes with many protons compared to the number of neutrons tend to be radioactive.

Analyse

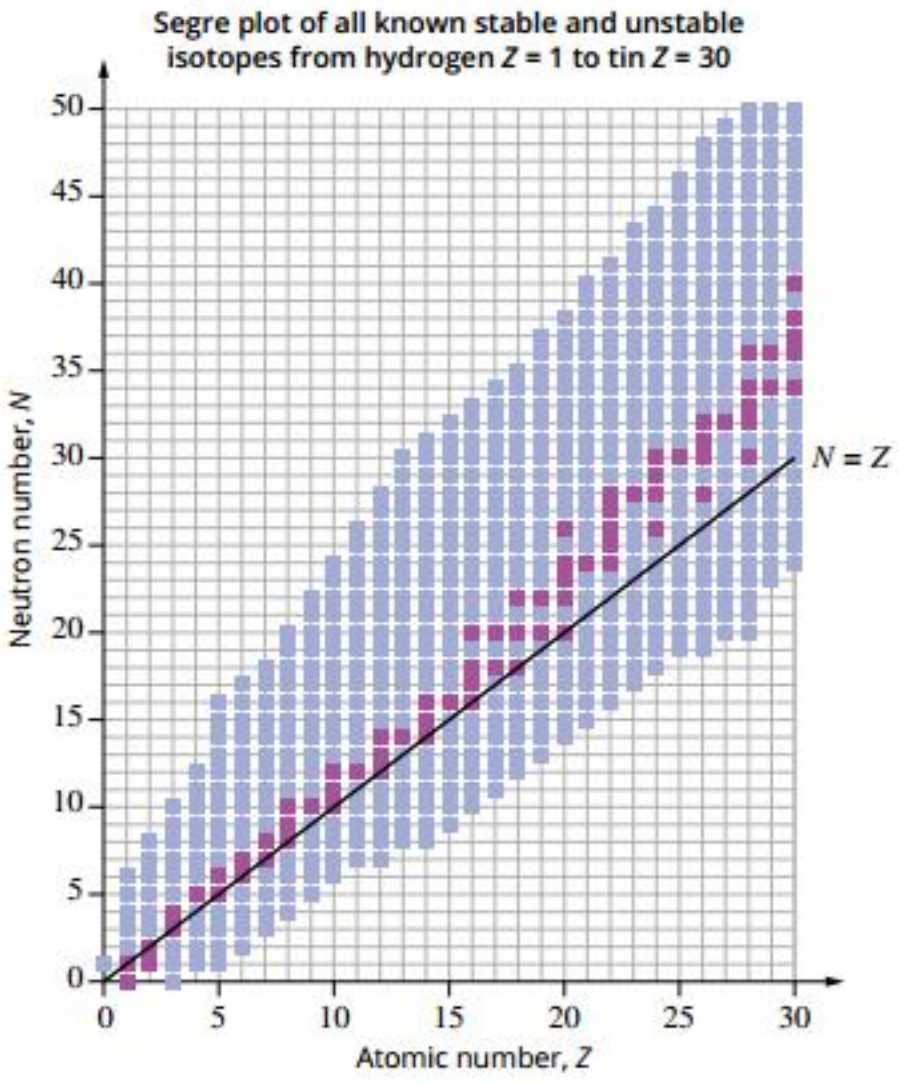
9 Bromine-79 is stable, but bromine-76 is radioactive. Imagine that you have just one atom of each isotope.

- **a** Deduce whether their atomic numbers and mass numbers are the same or different. Justify your answers.
- **b** Compare the way these atoms would interact chemically with other atoms.

10 $^{204}_{80}$Hg is a stable nuclide of mercury and $^{205}_{80}$Hg is a radioactive nuclide of mercury. Consider why the second nuclide is unstable.

11 $^{1}_{1}$H and $^{3}_{2}$He are the only known stable nuclides that have more protons than neutrons. State a reason why these nuclides might be stable.

12 Consider the Segre plot below and the periodic table in Figure 3.2.2 on page 50 to help you answer the following questions.

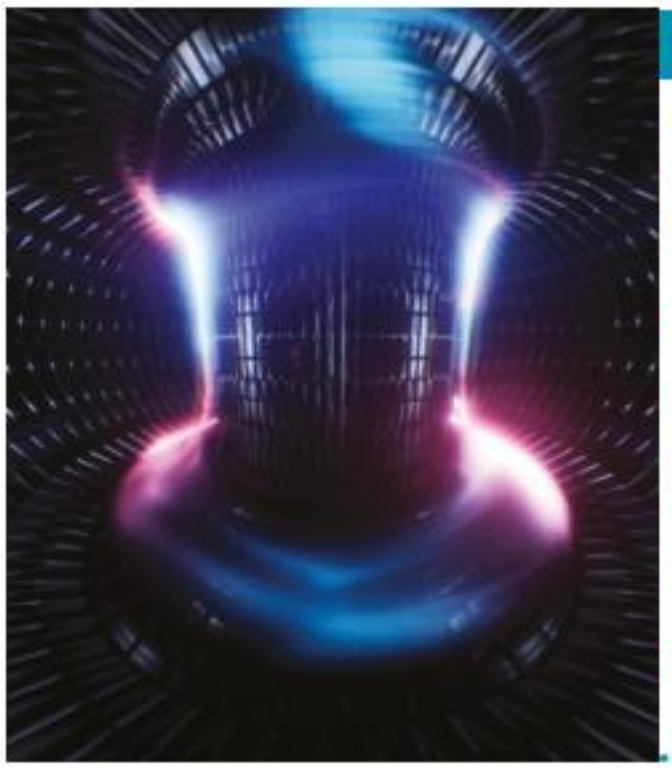


- **a** How many stable isotopes have more protons than neutrons? Name them.
- **b** Determine the mass number of the only stable isotope of beryllium ($Z = 4$).
- **c** How many stable nuclides have a neutron number of 22?
- **d** How many stable isotopes are there of iron ($Z = 26$)?
- **e** Identify the heaviest stable nuclide that has an equal number of protons and neutrons in its nucleus.

13 Using the Segre plot in Question 12, deduce whether the following nuclides are stable or radioactive. For any nuclides that are radioactive, state how they might decay to give a more stable nuclide.

- **a** $^{36}_{16}$S
- **b** $^{33}_{13}$Al
- **c** $^{58}_{27}$Co
- **d** $^{20}_{9}$F
- **e** $^{1}_{0}$n

3.3 Nuclear decay



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that nuclear decay is a process in which a radioactive nucleus becomes more stable by emitting energy, particles, or both
- distinguish between the three main types of radioactive decay—alpha, beta and gamma—in terms of energy, particles created and penetrating ability
- describe the particles produced in each of the three main types of radioactive decay
- describe ionising radiation and its effects
- understand that transmutation is the process of changing one element into another element
- write equations and predict the particles created in alpha, beta and gamma decay reactions
- understand that in any nuclear reaction both atomic number and mass number are conserved.

In the previous module it was explained why some nuclei are unstable by looking at general patterns in the numbers of protons and neutrons in the nucleus. In this module it will be shown that unstable nuclei become more stable by natural decay, in which unstable nuclei emit particles or energy or both.

ALPHA, BETA AND GAMMA DECAY

Any unstable nuclei will spontaneously decay into lighter nuclei. Heavier nuclei have more energy than they need and will become more stable by the emission of one or more particles, or electromagnetic waves. In this way, the unstable nucleus loses energy and becomes more stable.

In the early experiments with radioactivity, emissions from a sample of radium were directed through a magnetic field (Figure 3.3.1). The emissions followed three distinct paths, which suggested that three different forms of radiation were being emitted. The emissions each had different charges, masses and speeds.

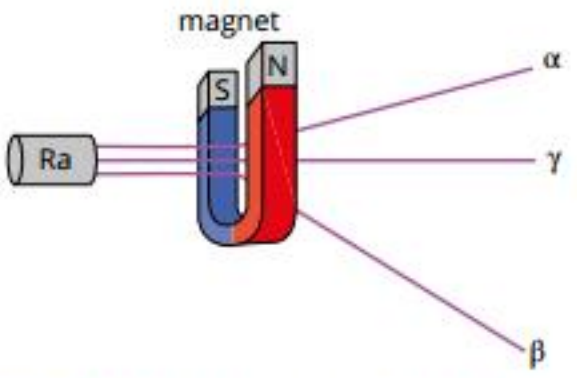


FIGURE 3.3.1 Applying a magnetic field shows that there are three different types of emissions from a radium source.

Transmutation

In many types of decay, a radioactive nucleus will lose one or more particles to become stable. The nucleus that is unstable is known as the **parent nucleus**. The particles that the parent nucleus emits may be any subatomic particle, leaving behind a nucleus called the **daughter nucleus**.

If the parent nucleus loses a proton or a neutron, the mass number of the daughter nucleus will be different. If the parent nucleus loses a proton, then the atomic number of the daughter nucleus will be different, which means that a new element has been created. When this occurs naturally, the process of creating a new element is called **transmutation** or **nuclear transmutation**. Transmutation occurs naturally in decay reactions, but it can be forced to occur as **artificial transmutation** in particle accelerators and nuclear reactors.

Transmutation is the process of creating a new element by changing the number of protons in a nucleus.

Worked example 3.3.1

TRANSMUTATION

The following isotopes are radioactive and each decays via the process described. Write the nuclide and isotope of the daughter nucleus formed. For part **b**, determine if the daughter nucleus is stable.	
a Molybdenum-101 is a radioactive isotope of the element molybdenum. It becomes more stable via a decay process in which one of its neutrons spontaneously turns into a proton.	
Thinking	**Working**
Molybdenum-101 can also be written as $^{101}_{42}$Mo. From this, the number of protons and neutrons in the nuclide can be determined. (The periodic table of elements is shown in Figure 3.2.2.)	$Z = 42$ $A = 101$ So, $N = A - Z = 101 - 42 = 59$
One of the neutrons of molybdenum-101 turns into a proton. This means that the number of neutrons in the daughter nucleus decreases by one, and the number of protons increases by one.	New N = old $N - 1 = 59 - 1 = 58$ New Z = old $Z + 1 = 42 + 1 = 43$
From the periodic table in Figure 3.2.2, it is seen that atomic number 43 is technetium, Tc.	$Z = 43$ is technetium, Tc
Write the isotope mass number, which is the sum of the atomic number and neutron number.	$A = Z + N = 43 + 58 = 101$
Write the nuclide using $^{A}_{Z}$X notation.	$^{101}_{43}$Tc or ^{101}Tc
Write using isotope name notation.	Technetium-101
b Americium-241 is also radioactive and is used in non-photoelectric smoke detectors. It decays by the emission of two protons and two neutrons.	
Thinking	**Working**
Americium-241 can also be written as $^{241}_{95}$Am. From this the number of protons and neutrons in this nuclide can be determined. (The periodic table of elements is shown in Figure 3.2.2.)	$Z = 95$ $A = 241$ So, $N = A - Z = 241 - 95 = 146$
Americium-241 emits two protons and two neutrons in its decay process. This means that $^{241}_{95}$Am loses two protons and two neutrons from its nucleus. Its daughter nuclide will have an atomic number two less than 95 and a neutron number two less than 146.	New N = old $N - 2 = 146 - 2 = 144$ New Z = old $Z - 2 = 95 - 2 = 93$
From the periodic table in Figure 3.2.2, it is seen that atomic number 93 is neptunium, Np.	$Z = 93$ is neptunium, Np

Write the isotope mass number, which is the sum of the atomic number and neutron number.	$A = Z + N = 93 + 144 = 237$
Write the nuclide is using ${}^{A}_{Z}X$ notation.	${}^{237}_{93}Np$ or ${}^{237}Np$
Write using isotope name notation.	Neptunium-237
Neptunium has an atomic number greater than 82, and, from Figure 3.2.2, it is seen that this means all neptunium isotopes are radioactive. Also, the Segre plot in Figure 3.2.7 shows that there are no stable (yellow) isotopes beyond atomic number 82, so neptunium-237 is radioactive.	Neptunium-237 is radioactive because its atomic number, 93, is higher than the heaviest stable element, lead-82.

➤ Try yourself 3.3.1

TRANSMUTATION

The following isotopes are radioactive and each decays via the process described in brackets. Write the nuclide and isotope of the daughter nucleus formed and determine if it is stable. You may use the periodic table in Figure 3.2.2 or Segre plot on page 53 to help you.

a ${}^{28}_{12}Mg$ (decays when a proton spontaneously turns into a neutron)

b ${}^{8}_{3}Li$ (decays when a neutron spontaneously turns into a proton)

c ${}^{222}_{86}Rn$ (decays when two protons and two neutrons are emitted)

You might have noticed that in each of the decay examples involving protons and neutrons turning into each other the mass number did not change. This is because both particles are nucleons and these nuclei are not changing the *total* number of nucleons, just the number of each type.

Ionising radiation

In Module 3.2, you were shown some examples of particles that are changed or emitted from a radioactive nucleus. As well as particles, an unstable nucleus can also emit energy in the form of electromagnetic radiation, or waves (typically X-rays, gamma rays and some ultraviolet radiation). This radiation is often very high in energy and when it interacts with matter it can completely remove electrons from an atom. This process is known as **ionisation** and the radiation that causes it is known as **ionising radiation**.

Ionising radiation is quite dangerous to living tissue, because the ionised atoms that are left behind after the radiation are very reactive and seek out molecules to combine with. If this occurs in the nuclei of vulnerable cells, unwanted chemical reactions can take place, which can cause cancer.

Alpha particles are the nuclei of helium-4 atoms and are, therefore, strongly positively charged. If an alpha particle passes through air, it will remove two electrons from any oxygen or nitrogen molecule in the air and leave it with a positive charge. The alpha particles are said to have ionised the air (Figure 3.3.2).

Lower-energy electromagnetic radiation such as radio waves, microwaves, infrared, visible light and ultraviolet-A radiation is non-ionising. Exposure to this radiation, even in significant amounts, has no serious consequences. Non-ionising radiation does not have enough energy to change the chemistry of the atoms and molecules that make up body cells.

Ionising radiation is a particle or type of energy that can cause electrons to be removed from an atom, thereby leaving it charged. Alpha particles, beta particles, neutrons and high-energy electromagnetic radiation such as ultraviolet rays, X-rays and gamma rays are all examples of ionising radiation.

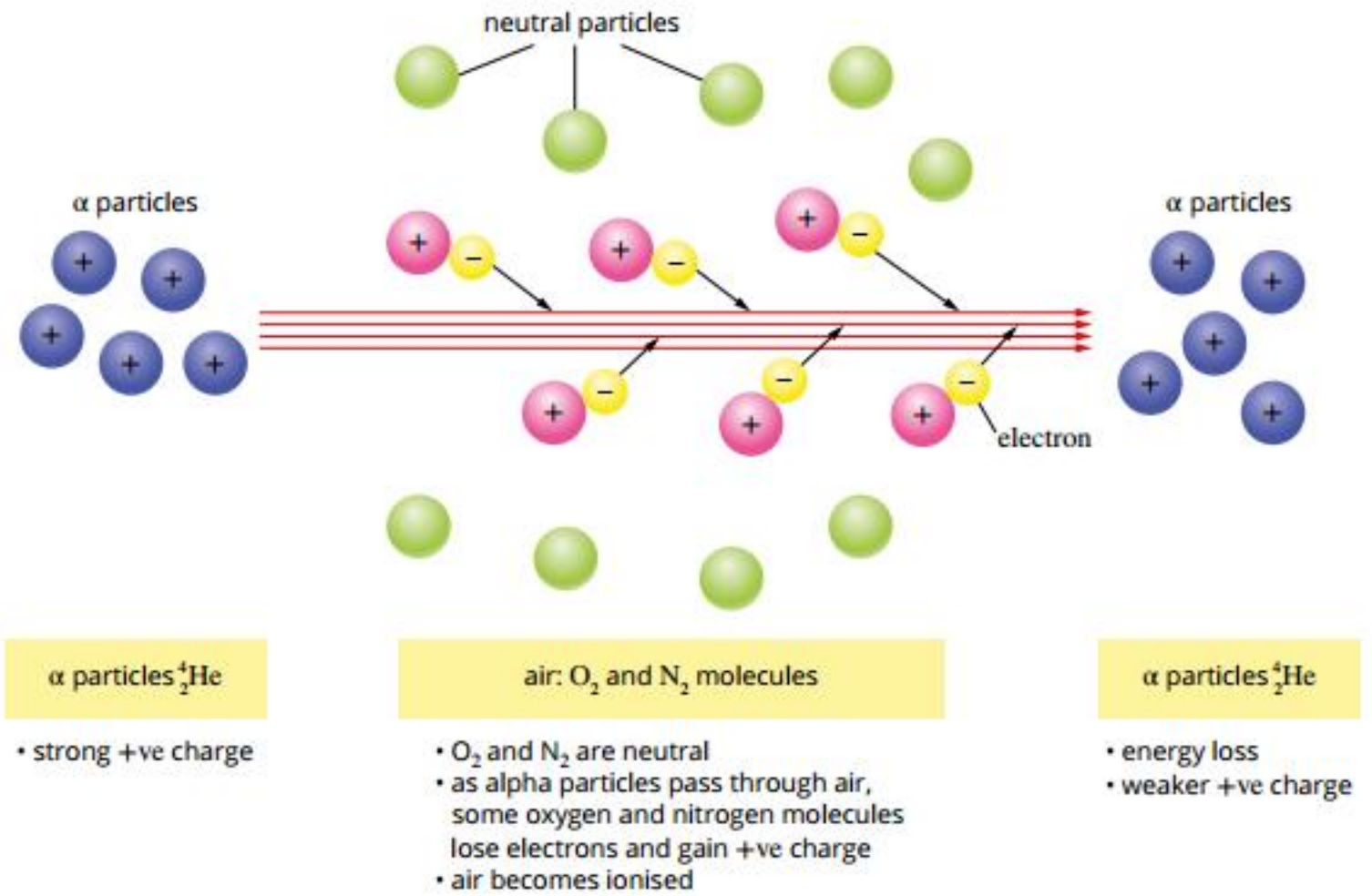

neutral particles
α particles
α particles
electron
α particles $^4_2$He
air: O_2 and N_2 molecules
α particles $^4_2$He
• strong +ve charge
• O_2 and N_2 are neutral
• as alpha particles pass through air, some oxygen and nitrogen molecules lose electrons and gain +ve charge
• air becomes ionised
• energy loss
• weaker +ve charge

FIGURE 3.3.2 Alpha particles ionise air particles.

Types of decay

There are three main types of natural nuclear decay. In all cases, the daughter nucleus is left with less energy than the parent nucleus. They are, in order of increasing energy:

- alpha decay
- beta decay
- gamma decay.

Table 3.3.1 summarises four main types of natural nuclear decay in terms of their charge, mass, ionising ability and ability to pass through matter (**penetrating ability**).

TABLE 3.3.1 The four main types of natural decay. Note that beta decay can be either beta$^+$ or beta$^-$ depending on the particles involved.

Decay type	Symbol	Particle or radiation	Charge	Mass	Emitted by	Ionisation ability	Penetrating ability
alpha	$^4_2$He or $^4_2\alpha$	particle (nucleus of helium-4 isotope)	+2	$6.644\,657 \times 10^{-27}$ kg 4.001 506 u	mostly radioactive isotopes heavier than lead ($Z = 82$)	high	low
beta$^+$	$^0_1\beta$ or ^0_1e	particle (high speed positron, or positively charged electron)	+1	$9.109\,384 \times 10^{-31}$ kg $5.485\,799 \times 10^{-4}$ u	most radioactive nuclei	medium	medium
beta$^-$	$^0_{-1}\beta$ or $^0_{-1}e$	particle (high speed electron)	−1	$9.109\,384 \times 10^{-31}$ kg $5.485\,799 \times 10^{-4}$ u	most radioactive nuclei	medium	medium
gamma	$^0_0\gamma$	radiation	0	0	most radioactive nuclei	low	high

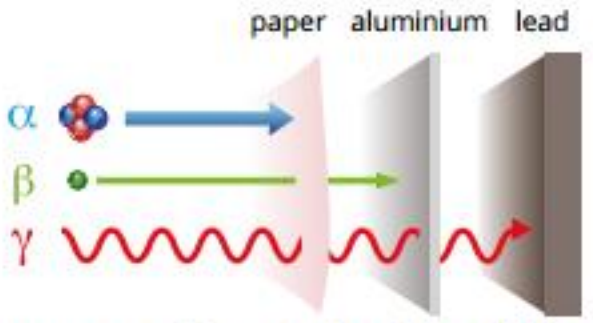


FIGURE 3.3.3 The penetrating abilities of alpha, beta and gamma radiation

The penetrating ability of each of the decay types is summarised in Figure 3.3.3. Alpha particles can travel only a few centimetres in air and cannot pass through a sheet of paper. Beta particles can also travel only a few centimetres in air; they can pass through a sheet of paper—meaning they have better penetrating ability than alpha particles—but they cannot pass through a thin sheet of aluminium. Gamma radiation can travel several kilometres in air; it can pass through paper and thin aluminium—meaning it has the best penetrating ability of the three—but it cannot pass through thick lead.

Other types of nuclear decay include electron capture (in which an inner electron is captured by the unstable nucleus causing a proton to turn into a neutron), or a single proton or neutron being emitted by the nucleus. These are relatively rare when compared to alpha, beta and gamma decay.

- Of the types of decay:
  - alpha radiation has the lowest penetrating ability but the highest ionising ability
  - gamma radiation has the highest penetrating ability but the lowest ionising ability.

Alpha decay

Alpha decay, or **alpha radiation**, occurs when a heavy, radioactive nucleus becomes more stable by emitting an alpha particle. The alpha particle is the nucleus of the helium-4 atom, which contains two protons and two neutrons and, therefore, has a doubly positive charge. It is one of the most stable particles in the universe.

An example of alpha decay is shown in Figure 3.3.4, in which a radioactive americium-241 nucleus decays by emitting an alpha particle to leave behind the daughter nucleus neptunium-237.

- Alpha decay occurs when a radioactive nucleus emits an alpha particle, $^{4}_{2}\text{He}$, a particle with two protons and two neutrons. The atomic number of the daughter nucleus decreases by two, and the mass number decreases by four.

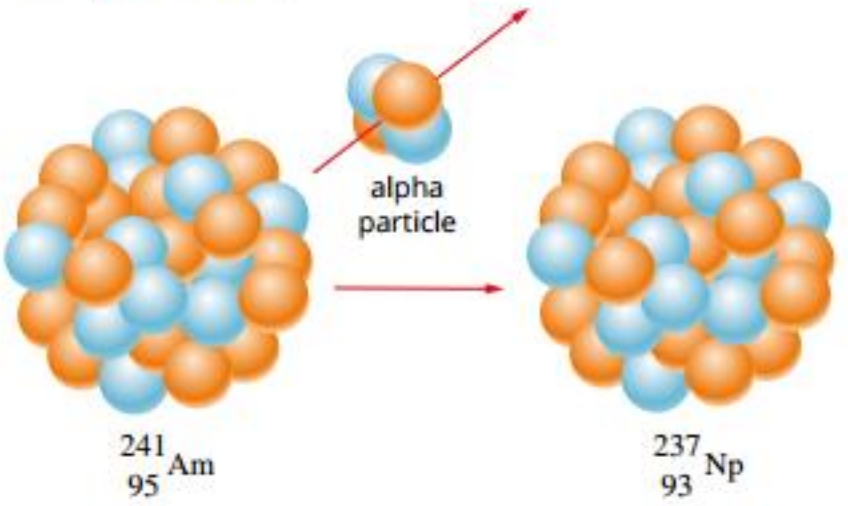


FIGURE 3.3.4 In this example of alpha particle decay, a radioactive nucleus gains some stability by expelling an alpha particle, or the nucleus of a helium-4 isotope.

During alpha decay, the radioactive parent nucleus emits an alpha particle, which carries away some of the excess energy. The resulting daughter nucleus has two fewer protons and two fewer neutrons. The mass number of the daughter nucleus is therefore four units less.

Alpha decay was first observed by Rutherford in 1899 and was used in his famous gold foil experiment. The alpha particles emitted by radioactive nuclei are the heaviest particles that can be emitted by a nucleus in any decay reaction. The large mass means that the alpha particle is relatively slow moving (up to 10% of the speed of light, or 30 000 km s^{-1}) and therefore has a lower than usual energy when compared to the other types of decay.

Alpha particles can be stopped by only a few centimetres of air, so they do not have a high penetrating ability and are generally safe to humans if exposure is outside of the body. If alpha-emitting nuclei are ingested into the body, however, then the proximity of the source of alpha particles to living tissue can be hazardous.

An alpha particle has low energy as well as a double positive charge, so it can ionise nearby atoms very easily. In fact, most of the helium found on Earth is from the alpha decay of heavy radioactive nuclei underground. The alpha particles emitted by this decay process ionise the oxygen or nitrogen in the air to make neutral helium gas.

Worked example 3.3.2

ALPHA DECAY

Identify the isotope of the daughter nucleus when plutonium-244 undergoes alpha decay.	
Thinking	**Working**
Plutonium-244 can also be written as $^{244}_{94}$Pu. From this the number of protons and neutrons can be determined.	$Z = 94$ $A = 244$ So, $N = A - Z = 244 - 94 = 150$
Alpha decay occurs when the parent nucleus loses two protons and two neutrons.	New N = old $N - 2 = 150 - 2 = 148$ New Z = old $Z - 2 = 94 - 2 = 92$
From the periodic table in Figure 3.2.2 it is seen that atomic number 92 is uranium, U.	$Z = 92$ is uranium, U
Write the isotope mass number, which is the sum of the atomic number and neutron number.	$A = Z + N = 92 + 148 = 240$
Write the nuclide is using $^{A}_{Z}X$ notation.	$^{240}_{92}U$ or ^{240}U
Write using isotope name notation.	Uranium-240

➤ Try yourself 3.3.2

ALPHA DECAY

Alpha decay mostly occurs in nuclei heavier than atomic number 82, but it also can occur in much lighter nuclei. $^{8}_{4}Be$ is an example of a very light radioactive nuclide that undergoes alpha decay.

Determine the daughter nuclide produced after this decay and name this nuclide.

Beta decay

Beta decay is the second type of natural decay that a radioactive nucleus may undergo to become more stable. It has two modes, which involve a spontaneous change of a nucleon:

- In **beta negative radiation** a neutron changes into a proton.
- In **beta positive radiation** a proton changes into a neutron.

The weak nuclear force (WNF) is responsible for beta decay. It allows the parent nucleus to become more stable by rearranging the number of protons and neutrons into a more energy-favourable ratio.

An example of beta negative radiation is shown in Figure 3.3.5, in which caesium-137 decays into barium-137 by the emission of a beta negative particle (a fast-moving electron) as well as an antineutrino.

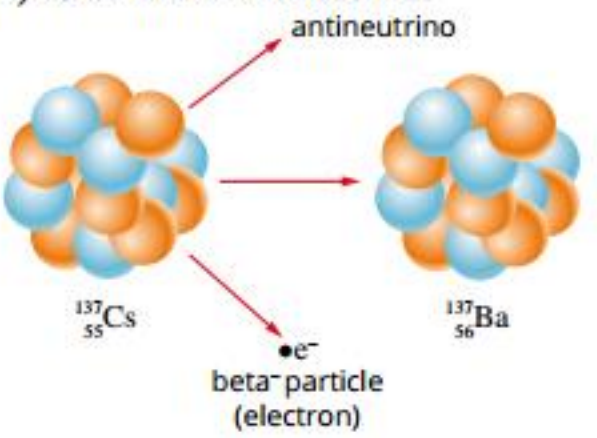


FIGURE 3.3.5 In this example of a beta negative decay, a radioactive nucleus gains some stability by emitting a beta negative particle (an electron) along with an antineutrino.

An example of beta positive radiation is shown in Figure 3.3.6, in which carbon-11 decays into boron-11 by the emission of a beta positive particle (a fast-moving **positron**) as well as a neutrino.

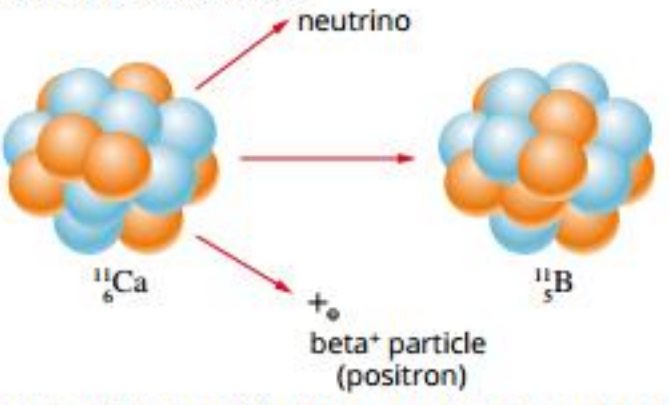


FIGURE 3.3.6 In this example of a beta positive decay, a radioactive nucleus gains some stability by emitting a beta positive particle (a positron) along with a neutrino.

- A **neutrino** ($^0_0\nu_e$) is a tiny, neutral and almost massless particle that is always seen in association with a positron.
- An **antineutrino** ($^0_0\bar{\nu}_e$) has almost the same properties as a neutrino but is always seen in association with an electron.

Both of these particles are now known to exist in gigantic numbers in the universe.

First observed in 1899, also by Rutherford, beta negative radiation occurs when the atomic number of the daughter nucleus increases by one and the neutron number decreases by one, giving no net change to the mass number of the daughter nucleus. This is a typical decay pattern for radioactive nuclei that have too many neutrons for the number of protons. These nuclei are *above* the darker, purple-coloured nuclei in the Segre plot in Figure 3.2.7 (page 52).

In 1934, French physicists Frederic and Irene Joliot-Curie (the daughter of Marie) first observed beta positive radiation. This occurs when one proton in the nucleus turns into a neutron. The atomic number of the daughter nucleus decreases by one and the neutron number increases by one, also giving no net change to the mass number of the daughter nucleus. This is a typical decay pattern for radioactive nuclei that have too many protons for the number of neutrons; they are *below* the darker, purple-coloured nuclei in the Segre plot in Figure 3.2.7 (page 52).

In both types of beta decay, when a nucleon spontaneously changes, the parent nucleus emits two other particles to carry away excess energy: a beta particle and a neutrino or antineutrino. The **beta particle** moves at approximately 99% of the speed of light.

- In beta negative radiation, the beta particle is a negatively charged electron ($^{0}_{-1}\beta$ or $^{0}_{-1}e$).
- In beta positive radiation, the beta particle is a positively charged positron ($^{0}_{1}\beta$ or $^{0}_{1}e$).

A positron is a particle with the same properties as the electron, except that it has a positive charge and does not make up everyday matter. Note that the electron emitted during beta negative decay comes directly from the nucleus, not from the electron cloud surrounding the nucleus.

The beta particle has a single positive or negative charge, so it moves very fast, is about 8000 times lighter than an alpha particle and its penetrating power is greater than that of the alpha particle. The beta particle can travel through a few metres of air or a few millimetres of aluminium foil before being absorbed.

The high speed of the beta particle also does not allow for it to ionise nearby atoms very well.

A summary of the two modes of beta decay is given in Table 3.3.2.

TABLE 3.3.2 A summary of the two modes of beta decay

Type of beta decay	Nuclear process	Daughter nucleus atomic number	Daughter nucleus neutron number	Daughter nucleus mass number	Particles emitted
beta positive	one proton changes into one neutron	one less than the parent's atomic number	one more than the parent's neutron number	same as parent nucleus	positron and neutrino ($^{0}_{1}\beta$ and $^{0}_{0}\nu_e$)
beta negative	one neutron changes into one proton	one more than the parent's atomic number	one less than the parent's neutron number	same as parent nucleus	electron and antineutrino ($^{0}_{-1}\beta$ and $^{0}_{0}\bar{\nu}_e$)

Beta negative decay occurs when a radioactive nucleus emits a high-speed electron, $^{0}_{-1}\beta$, and an antineutrino, $^{0}_{0}\bar{\nu}_e$. The atomic number of the daughter nucleus increases by one but the mass number stays the same.

Beta positive decay occurs when a radioactive nucleus emits a high-speed positron, $^{0}_{1}\beta$, along with a neutrino, $^{0}_{0}\nu_e$. The atomic number of the daughter nucleus decreases by one but the mass number stays the same.

Worked example 3.3.3

BETA DECAY

State the daughter nucleus and the particles emitted when the following beta decays occur.

a Caesium-137 undergoes beta negative decay.

Thinking	Working
Caesium-137 can also be written as $^{137}_{55}$Cs. From this the number of protons and neutrons can be determined.	$Z = 55$ $A = 137$ So, $N = A - Z = 137 - 55 = 82$
Beta negative decay occurs when a neutron in the parent nucleus turns into a proton.	New N = old $N - 1 = 82 - 1 = 81$ New Z = old $Z + 1 = 55 + 1 = 56$
From the periodic table in Figure 3.2.2, it is seen that atomic number 56 is barium, Ba.	$Z = 56$ is barium, Ba
To write the daughter isotope, the mass number is also needed, which is the sum of the atomic number and neutron number.	$A = Z + N = 56 + 81 = 137$
Write the nuclide using the $^{A}_{Z}$X notation.	$^{137}_{56}$Ba or ^{137}Ba
Write the element using name notation.	Barium-137
This is beta negative decay, so the particles emitted during this process are an electron and antineutrino.	An electron and antineutrino ($^{0}_{-1}\beta$ and $^{0}_{0}\bar{\nu}_e$) are emitted by the parent nucleus.

b Copper-64 undergoes beta positive decay.	
Thinking	**Working**
Copper-64 can also be written as $^{64}_{29}Cu$. From this the number of protons and neutrons can be determined.	$Z = 29$ $A = 64$ So, $N = A - Z = 64 - 29 = 35$
Beta positive decay occurs when a proton in the parent nucleus turns into a neutron.	New N = old $N + 1 = 35 + 1 = 36$ New Z = old $Z - 1 = 29 - 1 = 28$
From the periodic table in Figure 3.2.2, it is seen that atomic number 28 is nickel, Ni.	$Z = 28$ is nickel, Ni
To write the daughter isotope, the mass number is also needed, which is the sum of the atomic number and neutron number.	$A = Z + N = 28 + 36 = 64$
Write the nuclide using $^{A}_{Z}X$ notation.	$^{64}_{28}Ni$ or ^{64}Ni
Write the element using name notation.	Nickel-64
This is beta positive decay, so the particles emitted during this process are a positron and a neutrino.	A positron ($^{0}_{1}\beta$) and a neutrino and ($^{0}_{0}\nu_e$) are emitted by the parent nucleus.

➤ Try yourself 3.3.3

BETA DECAY

Predict the daughter nuclides and the particles emitted when the following isotopes decay via the processes indicated.

a Carbon-11 undergoes beta positive decay.

b A single neutron outside an atom undergoes beta negative decay.

Gamma decay

Gamma decay, or **gamma radiation**, was first observed by the French physicist Paul Villard in 1900 and is the third type of naturally occurring decay that allows a radioactive isotope to become more stable. Rather than the nucleus undergoing a change in the number of nucleons, gamma decay reduces the amount of energy an unstable nucleus has by emitting a **gamma ray**. The gamma ray is a very energetic part of the electromagnetic spectrum that travels at the speed of light ($3.00 \times 10^{8} m s^{-1}$) and carries off some of the excess energy of the radioactive nucleus, thereby making the nucleus more stable.

An example of gamma radiation is shown in Figure 3.3.7, where a radioactive plutonium-240 nucleus decays by emitting a gamma ray without any change in the number of nucleons.

Because they are an electromagnetic wave, gamma rays have no charge and no mass, so they do not cause a change in the number of protons or neutrons in the nucleus. Gamma rays are the most energetic of the particles or radiation emitted by a radioactive nucleus and, therefore, have a very high penetrating ability. This is so high that a few centimetres of lead are required to stop any gamma rays.

The direct ionising ability of gamma rays is quite low, as they are neutral and move at the speed of light. In fact, they will usually pass straight through tissue. They do, however, cause indirect ionisation through interaction with atoms and the subsequent beta particles they create.

i Gamma decay occurs when an energetic, radioactive nucleus emits a gamma ray, $^{0}_{0}\gamma$. There is no change to the mass number or atomic number of the daughter nuclide.

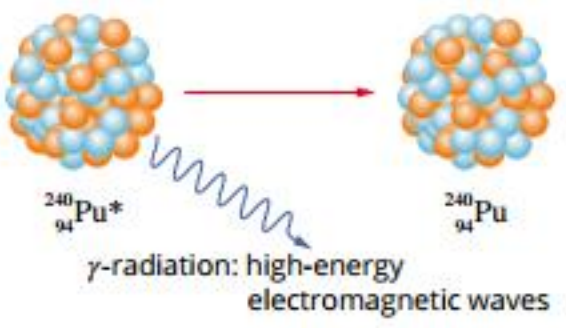


FIGURE 3.3.7 An example of gamma decay, by which a radioactive nucleus gains some stability by emitting energy in the form of a gamma ray. Note that the * indicates that a particular nuclide has an excess of energy when compared to the daughter nuclide.

DECAY REACTIONS

Alpha, beta and gamma decay can be conveniently written as nuclear equations, which show the atomic and mass numbers of the parent nucleus, daughter nucleus and emission products. In nuclear equations, the initial nuclides (reactants) are always on the left-hand side of an arrow showing the direction of the decay; the daughter nuclides and other products are on the right-hand side. Since decay is a way of reducing the instability of a parent nucleus, a decay reaction will always give off energy in the form of kinetic energy of the products, or electromagnetic radiation in gamma decay.

> **i** A decay equation is a short way of writing the reactants and products of any decay reaction. The mass numbers and atomic numbers are always conserved.

Alpha decay equations

Alpha decay equations are relatively simple to write because they only have one reactant and two products plus energy.

An example of an alpha decay reaction is shown below in Figure 3.3.8.

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} + \text{energy}$$

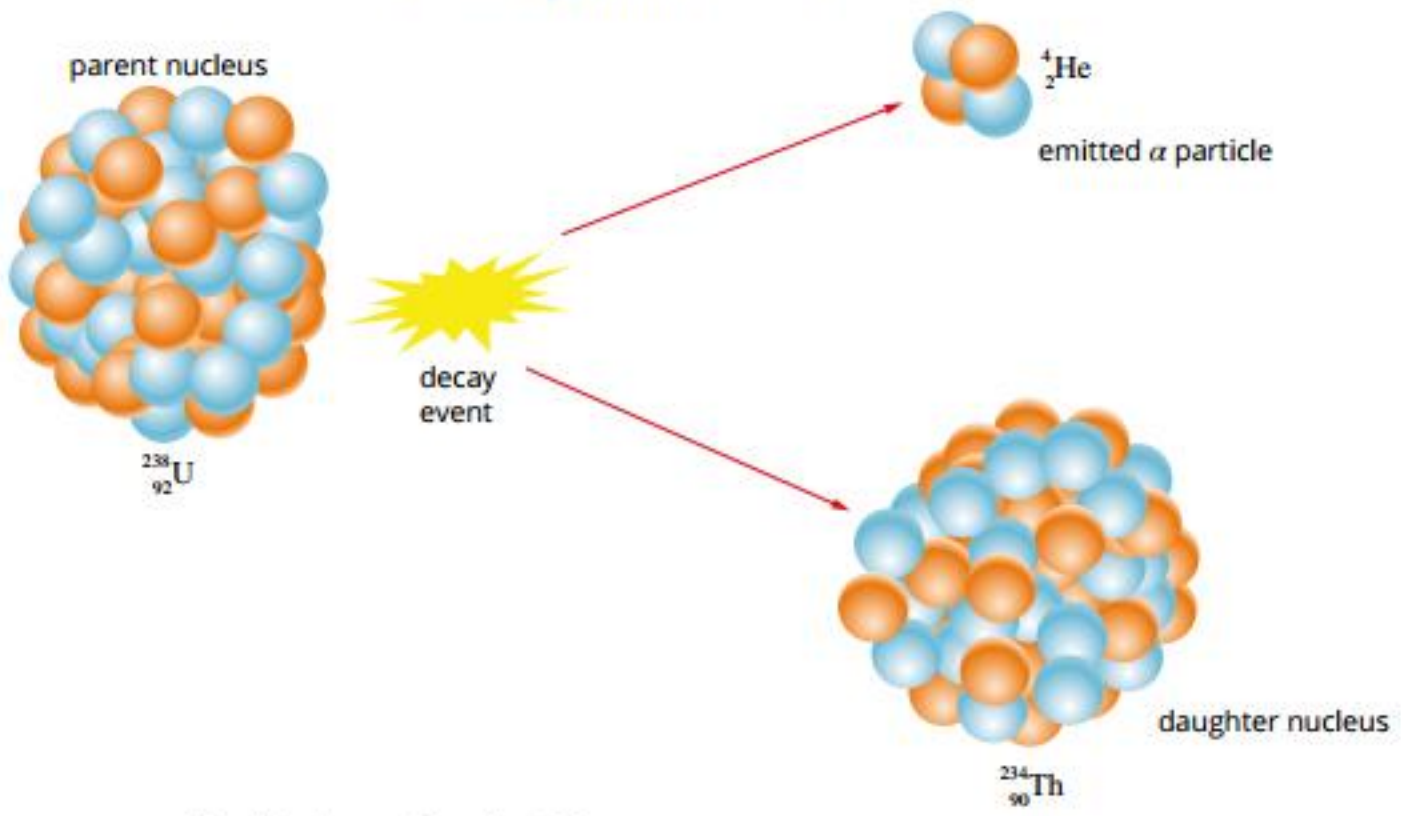


FIGURE 3.3.8 The alpha decay of uranium-238

This is a decay reaction, so there is only one reactant, the uranium-238. This is a natural decay process, so the arrow indicates that this reaction will take place to release energy and give two products: thorium-234 as the daughter isotope and the alpha particle $^{4}_{2}\text{He}$.

Note that in nuclear equations the mass numbers and atomic numbers are all conserved. This means that the total of the mass numbers on each side of the arrow are equal, and the total of the atomic numbers on each side are equal.

Because any decay reaction is going to result in the daughter nucleus becoming more stable by losing energy, energy appears on the right-hand side of the equation.

Beta decay equations

In beta decay equations, the conservation of mass and atomic numbers are especially important because there is a change in atomic number but no change in the mass number. Also keep in mind that in nuclear physics, an electron has an atomic number of −1.

Beta decay equations also have one reactant, but they have three products plus energy.

An example of a beta decay reaction is shown below in Figure 3.3.9 on the next page.

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_{e} + \text{energy}$$

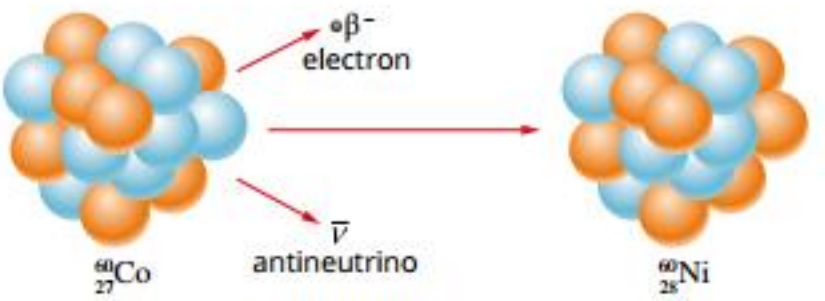


FIGURE 3.3.9 The beta negative decay of cobalt-60

Again, as with any decay equation, there is one reactant: the cobalt-60 isotope. You can see from the products that this is a beta negative decay because the daughter nucleus has gained a proton, and the other emitted particles are an electron and antineutrino.

Inside the cobalt-60 nucleus, a single neutron is undergoing the following reaction:

$$^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{H} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_{e}$$

An isotope that decays via beta positive decay is protactinium-230. This is shown in Figure 3.3.10 with the equation:

$$^{230}_{91}\text{Pa} \rightarrow {}^{230}_{90}\text{Th} + {}^{0}_{1}\beta + {}^{0}_{0}\nu_{e} + \text{energy}$$

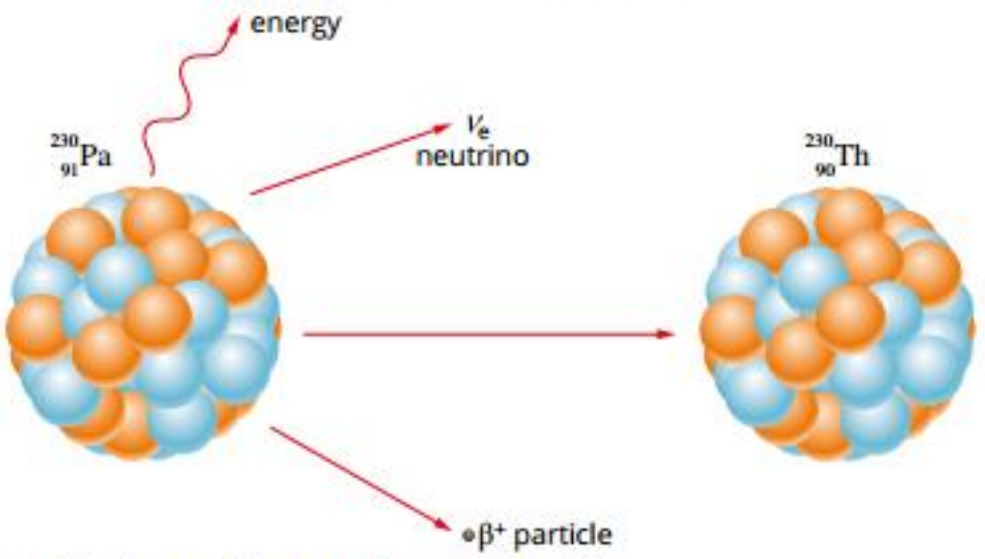


FIGURE 3.3.10 The beta positive decay of protactinium-230

In this reaction, mass numbers are conserved: 230 = 230 + 0 + 0

The atomic numbers are also conserved: 91 = 90 + 1 + 0

With all beta decay the mass number does not change, so you expect the two emitted particles—the beta particle and neutrino/antineutrino—to have very little mass compared to the parent and daughter nuclei. Inside the protactinium-230 nucleus, one proton undergoes the following reaction:

$$^{1}_{1}\text{H} \rightarrow {}^{1}_{0}\text{n} + {}^{0}_{1}\beta + {}^{0}_{0}\overline{\nu}_{e}$$

Gamma decay equations

Gamma decay equations are the most straightforward decay equations to write. This is because there is no change in mass number or atomic number, so the parent and daughter nuclei are basically the same apart from a decrease in the energy of the parent nucleus.

To distinguish the parent nucleus from the daughter nucleus in gamma decay, an asterisk (*) is used to indicate that the parent nucleus has more energy than the daughter nucleus.

An example of a gamma decay reaction occurs when xenon-131* emits a gamma ray to become stable, as shown in Figure 3.3.11. The equation is:

$$^{131}_{54}\text{Xe}^{*} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{0}\gamma$$

The element xenon has not changed in gamma decay; the mass number is 131, and the atomic number is 54. The * is used to indicate the unstable $^{131}_{54}Xe^*$ nucleus before it emits the gamma ray and energy to become stable.

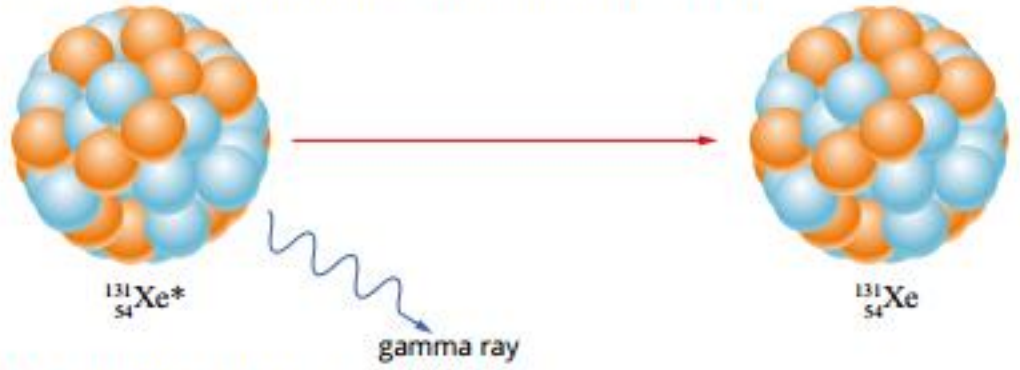


FIGURE 3.3.11 The gamma decay of xenon-131*

Worked example 3.3.4

RADIOACTIVE DECAY 1

Strontium-90 decays by radioactive emission to form yttrium-90. The equation for this is:

$$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + X$$

where X is the emitted particle or particles. Determine the atomic and mass numbers for X and hence identify the type of radiation being emitted.

Thinking	Working
The mass numbers of 90 are already balanced so the mass number of X, A_x, must be 0.	Left-hand side $A = 90$ Right-hand side $A = 90 + A_x$ $90 = 90 + A$ $A = 90 - 90 = 0$
The atomic numbers are not balanced, so the atomic number of X, Z_X, needs to be found.	Left-hand side $Z = 38$ Right-hand side $Z = 39 + Z_x$ $38 = 39 + Z_x$ $Z_x = 38 - 39 = -1$
X has atomic number of –1, and a mass number of zero.	X is an electron, $^{0}_{-1}\beta$, and is emitted in beta negative radiation along with an antineutrino, $^{0}_{0}\bar{\nu}_e$.

➤ Try yourself 3.3.4

RADIOACTIVE DECAY 1

Polonium-218 decays by emitting an alpha particle followed by a gamma ray. The nuclear equation of the alpha decay is:

$$^{218}_{84}Po \rightarrow X + ^{4}_{2}\alpha$$

Determine the atomic number and mass number of X, and then use the periodic table in Figure 3.2.2 to identify the element.

Worked example 3.3.5

RADIOACTIVE DECAY 2

Determine the unknown particles or nuclei in the following incomplete reactions and identify the type of decay that is occurring.

a $^{192}_{78}Pt^* \rightarrow X + {}^{0}_{0}\gamma$

THINKING	WORKING
The mass numbers must be balanced so that 192 on the left-hand side is equal to the sum of the mass numbers on the right-hand side. A_x is the mass number of X.	$192 = A_x + 0$ The mass number of X is 192.
The atomic numbers must also be balanced, so that 78 on the left-hand side is equal to the sum of atomic numbers on the right-hand side. Z_X is the atomic number of X.	$78 = Z_X + 0$ The atomic number of X is 78.

b $^{47}_{24}Cr \rightarrow {}^{47}_{23}V + X + {}^{0}_{0}\nu_e$

THINKING	WORKING
The mass numbers must be balanced so that 47 on the left-hand side is equal to the sum of 47, zero and the mass number of particle X, A_x, on the right-hand side.	$47 = 47 + A_x + 0$ So, the mass number of X is zero.
The atomic numbers must also be balanced so that 24 on the left-hand side is equal to the sum of 23, zero and the atomic number of particle X, Z_x, on the right-hand side.	$24 = 23 + Z_x + 0$ So, the atomic number of X is 1 and it is therefore a positron, ${}^{0}_{1}\beta$.
Identify the type of decay. Note that on the right-hand side of the equation is a neutrino, ${}^{0}_{0}\nu_e$.	This decay type is beta positive decay because neutrinos are always associated with positrons.

➤ Try yourself 3.3.5

RADIOACTIVE DECAY 2

Determine the unknown particles or nuclei in the following incomplete reactions and identify the type of decay that is occurring.

a $^{242}_{96}Cm \rightarrow X + {}^{4}_{2}He$

b $^{35}_{16}S \rightarrow {}^{35}_{17}Cl + X_1 + X_2$

c $X_1 \rightarrow {}^{290}_{116}Lv + {}^{4}_{2}He + X_2$

Decay series

A decay series is a sequence of various radioactive decays by successive daughter nuclei that eventually forms a stable nuclide.

Every radioactive nucleus has an excess of energy. The process of decay removes some of that energy so that a more stable daughter nucleus remains. Quite often the daughter nucleus itself is also radioactive, so it will also decay, producing a 'grand-daughter' nucleus. This is known as a **decay series** and will always continue if the successive daughter nuclei are radioactive. A decay series ends when the daughter nucleus is stable. Note that most radioactive isotopes have several different pathways of obtaining a stable isotope and many of them involve many individual decay reactions.

Examples of decay series include the decay series of uranium-238, which ends in the stable isotope lead-206, and of actinium-235, which eventually ends with lead-207.

The decay of thorium-232 is an example of a decay series that has 10 distinct decay reactions. It ends in the stable isotope lead-208:

$$^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He}$$

$$^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_e$$

$$^{228}_{89}\text{Ac} \rightarrow {}^{228}_{90}\text{Th} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_e$$

$$^{228}_{90}\text{Th} \rightarrow {}^{224}_{88}\text{Ra} + {}^{4}_{2}\text{He}$$

$$^{224}_{88}\text{Th} \rightarrow {}^{220}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

$$^{220}_{86}\text{Rn} \rightarrow {}^{216}_{84}\text{Po} + {}^{4}_{2}\text{He}$$

$$^{216}_{84}\text{Po} \rightarrow {}^{212}_{82}\text{Pb} + {}^{4}_{2}\text{He}$$

$$^{212}_{82}\text{Pb} \rightarrow {}^{212}_{83}\text{Bi} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_e$$

$$^{212}_{83}\text{Bi} \rightarrow {}^{208}_{81}\text{Tl} + {}^{4}_{2}\text{He} \text{ or } {}^{212}_{83}\text{Bi} \rightarrow {}^{212}_{84}\text{Po} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_e$$

$$^{208}_{81}\text{Tl} \rightarrow {}^{208}_{82}\text{Pb} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_e \text{ or } {}^{212}_{84}\text{Po} \rightarrow {}^{208}_{82}\text{Po} + {}^{4}_{2}\text{He}$$

This is shown graphically in Figure 3.3.12. Note that the final reaction has two pathways but both finish with the stable isotope lead-208.

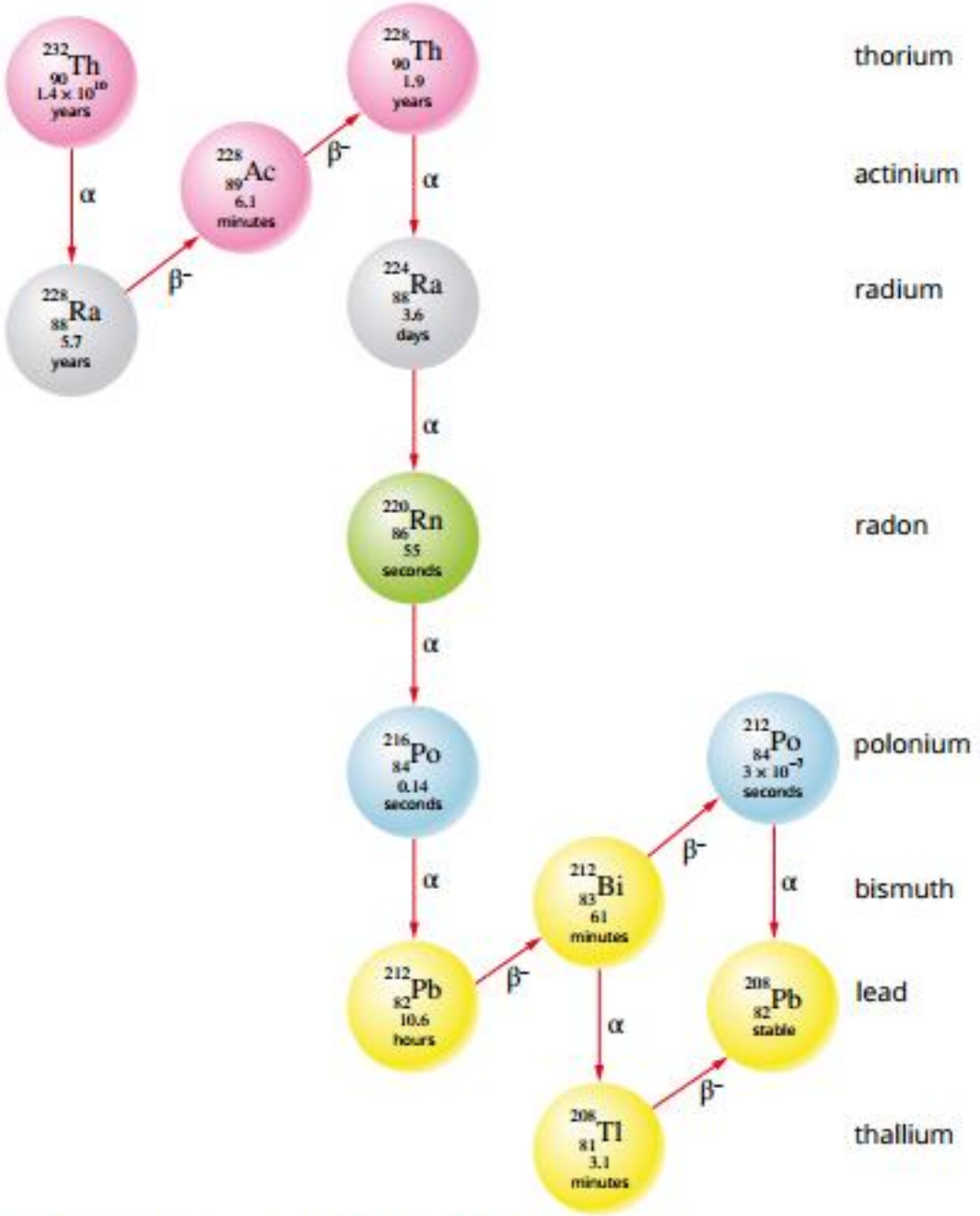


FIGURE 3.3.12 The decay series of thorium-232 into stable lead-208

Decay series are used in radioactive dating of rocks to obtain a reasonable estimate of the age of a rock by comparing the relative abundances of each element in the series to how much is expected after a given time.

3.3 Review

SUMMARY

- All decay reactions involve a parent nucleus losing energy to become a more stable daughter nucleus.
- There are three main types of decay: alpha, beta and gamma.
- Ionisation is the process in which an atom loses or gains electrons to become positively or negatively charged.
- When ionising radiation passes through human tissue, it may ionise atoms and molecules in the body's cells, which can lead to the development of cancerous cells.
- Transmutation is the process of changing one element into another.
- An alpha particle consists of two protons and two neutrons, and has relatively low penetrating ability but high ionising ability.
- Beta radiation has medium penetrating ability and medium ionising ability.
- Beta positive radiation specifically involves a proton turning into a neutron with the emission of a positron and neutrino.
- Beta negative radiation specifically involves a neutron turning into a proton with the emission of an electron and antineutrino.
- Gamma radiation involves the emission of a high-energy gamma ray from a radioactive nucleus without a change in mass or atomic number. Gamma radiation has very high penetrating ability but low ionisation ability.
- The decay of a radioactive nucleus can be written using a nuclear equation where the mass number and atomic numbers are both conserved.
- A daughter nucleus will also decay if it is not stable and this process will continue in a series until a stable nucleus is formed.

KEY QUESTIONS

Describe

1 Describe the positron particle.

2 Identify the type of radiation (alpha, beta or gamma) that can penetrate human skin but not 3 mm of aluminium.

3 Order alpha, beta and gamma radiation, from most to least penetrating power.

4 Order alpha, beta and gamma radiation, from smallest to largest mass.

5 Identify the type of radiation (alpha, beta or gamma) that:

a can penetrate aluminium foil

b is ejected when a neutron decays into a proton

c travels relatively slowly at around 10% of the speed of light

d travels at speeds of up to 90% of the speed of light

e has no charge.

6 State whether the isotope formed at the end of a decay series is stable or unstable.

7 Name the nucleon that transforms into a proton during beta negative decay.

Apply

8 Describe the difference between the two types of beta decay.

9 Briefly explain why alpha particles have very poor penetrating ability.

10 Explain why the sum of the mass numbers is conserved in decay reactions.

11 Explain why beta particles, not alpha or gamma, are the best to use for monitoring the thickness of thin metal sheets.

Analyse

12 Determine the type of radiation (alpha, beta or gamma) that would be used to treat brain cancer, where the radiation needs to penetrate the skull and reach the site of the tumour.

13 For the unknown nuclides X and Y in each of the following decay equations, determine the atomic number and mass number, then use the periodic table in Figure 3.2.2 to identify the unknown elements.

a $^{235}_{92}U \rightarrow {}^{4}_{2}He + X$

b $^{228}_{88}Ra \rightarrow Y + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}$

14 Carbon-14 decays by beta negative emission to form nitrogen-14. The equation for this is:

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta + ^{0}_{0}\bar{\nu}$$

a Determine how many protons and neutrons the nitrogen-14 isotope has.

b Determine which nucleon on the left side of the equation has transformed into what other nucleon or particle(s) on the right side of the equation.

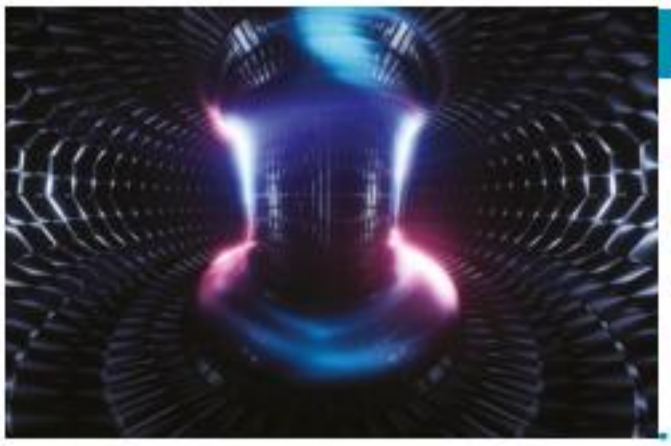
15 Identify the particle that is represented by X and Z in each of the following decay equations.

a $^{45}_{20}Ca \rightarrow ^{45}_{21}Sc + X + Z$

b $^{150}_{70}Yb \rightarrow ^{146}_{68}Er + X$

c $X \rightarrow ^{236}_{92}U + ^{4}_{2}He$

3.4 Half-life



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that the rate of decay of a radioisotope is measured by its half-life, $t_{\frac{1}{2}}$; this is the time that it takes for half of the radioisotope to decay
- calculate the number of nuclei remaining, using the half-life equation $N = N_0\left(\frac{1}{2}\right)^n$ from the number of half-lives elapsed
- use a graph of the number of radioactive nuclei remaining to determine the half-life of an isotope.

A radioactive nucleus decays by releasing energy or energy and other particles. The remaining daughter nucleus is more stable as a result. For an individual nucleus, this decay occurs randomly and is governed by the laws of quantum physics, but you can obtain information on how long it takes a large sample of a radioactive substance to decay.

When the number of nuclei in a sample of radioactive nuclei is graphed against time, a curved line is produced (Figure 3.4.1). This is an example of an exponential decay curve. Such curves have three important features:

- The number of undecayed nuclei is decreasing at a decreasing rate.
- The *y*-intercept of the graph represents the number of undecayed nuclei at time zero (the initial number of undecayed nuclei).
- The graph approaches but never reaches zero even after an infinite time. However, in nuclear decay if one nucleus remains and it decays, then there will be no nuclei left. (See Worked example 3.4.1.)

A graph of original nuclei remaining against time is a curve that decreases at a decreasing rate.

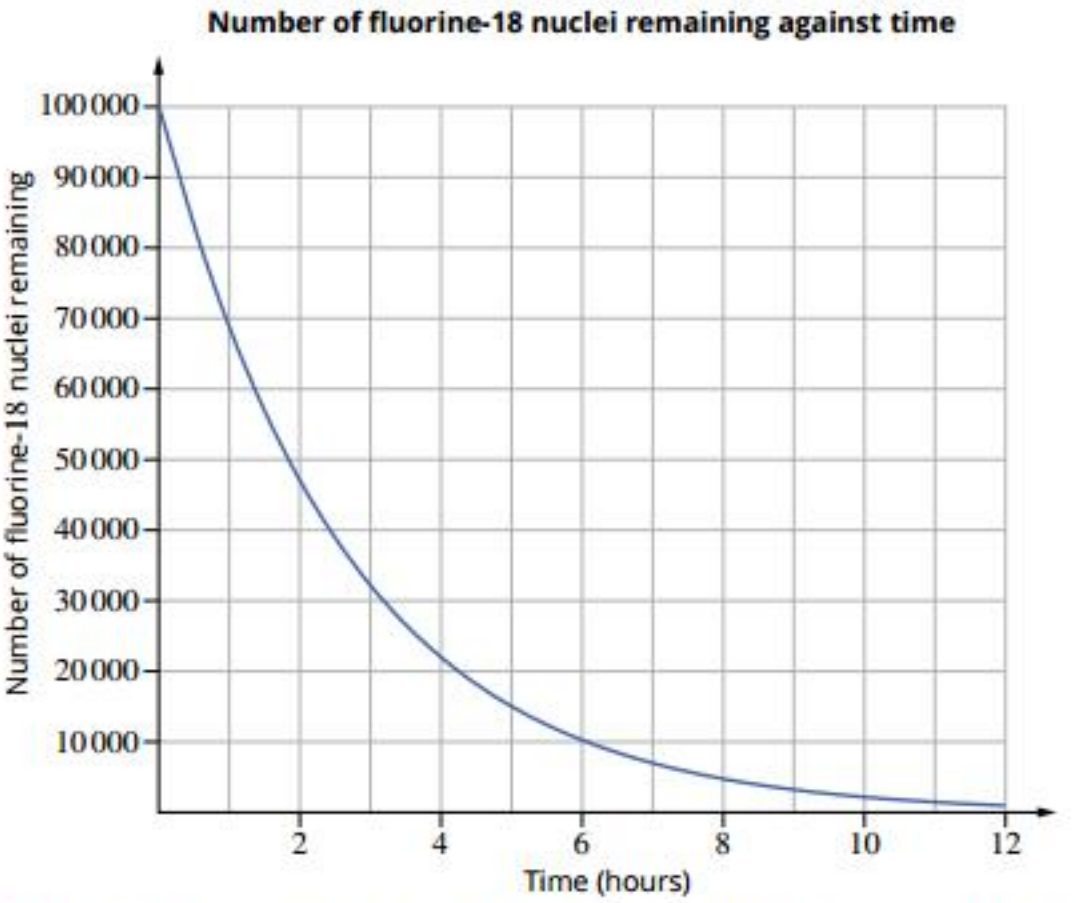


FIGURE 3.4.1 A graph that plots the undecayed nuclei of fluorine-18 against time produces a curve like this. This type of graph is known as an exponential decay curve.

HALF-LIFE CURVES

If the mass of all the original nuclei is graphed, instead of the numbers of nuclei, then the same-shaped exponential decay curve would result. The time taken for exactly half of the original number of nuclei to decay is called the **half-life**, $t_{\frac{1}{2}}$. Half-life is measured in a time unit and is not specifically linked to seconds. This means that after one half-life, exactly half of the nuclei have decayed. After another half-life, half of the remaining nuclei decay, so $\frac{1}{4}$ of the original number of nuclei remain. After another half-life, $\frac{1}{8}$ of the original nuclei remain, and so on. Note that this does not imply that after two half-lives there is nothing remaining of the original nuclei, because the half-life is always measured with respect to the number remaining at the time.

Figure 3.4.2 shows the decay of polonium-218. If there are 100 million nuclei of polonium-218 nuclei at the start of a measurement, then after one half-life (3.1 minutes for polonium-218) the number of nuclei remaining will have dropped to 50 million. Over the next 3.1 minutes this number drops to 25 million and so on.

As time passes, a smaller and smaller proportion of the original radioisotope remains in the sample. Even a very small radioactive sample will contain billions of atoms. It is important to know that although the behaviour of such a large sample of nuclei can be mathematically predicted, the behaviour of one particular nucleus cannot. It has a 50% chance of decaying in each half-life.

The half-life of a radioactive nucleus is an indication of how stable it is. The shorter the half-life of a nucleus the more unstable it is, and the longer the half-life, the more stable the nucleus is. All stable isotopes effectively have an infinite half-life because they basically do not ever decay.

Also, the half-life of a radioisotope is constant and cannot be changed by chemical reactions, heat and so on. Half-life is solely determined by the instability of the nuclei of the radioisotope.

Table 3.4.1 lists selected radioisotopes, their decay modes, half-lives and notes. Note that hydrogen-7 does not decay via one of the three main types of radiation.

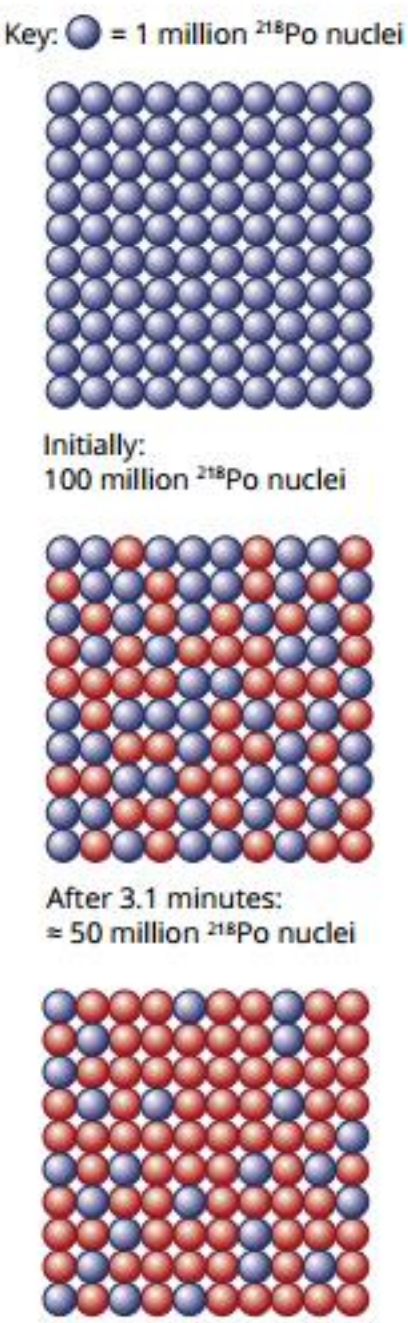


FIGURE 3.4.2 The decay of polonium-218 over two half-lives showing how only one quarter (25%) of the original radioisotope remains after two half-lives

TABLE 3.4.1 Selected isotopes

Isotope	Decay type	Half-life	Notes
tellurium-128	beta negative	2.2×10^{24} years	longest known half-life of any radioactive isotope
uranium-238	alpha	4.7×10^{9} years	used as a fuel in nuclear reactors and rock dating
potassium-40	beta negative	1.2×10^{9} years	the largest source of natural radioactivity in the human body
plutonium-239	alpha	24 110 years	used as a fuel in nuclear reactors and in nuclear weapons
carbon-14	beta negative	5730 years	used in carbon dating of fossils and in archaeology
americium-241	alpha	432 years	used in smoke alarms
strontium-90	beta negative	28.8 years	used in cancer therapy, energy in space probes and is a large component of the fallout from the Chernobyl and Fukushima nuclear reactor disasters
tritium (hydrogen-3)	beta negative	12.3 years	used as a fuel in nuclear fusion research and in nuclear weapons
astatine-210	beta positive	8.1 hours	the most stable isotope of the rarest naturally occurring element on Earth
beryllium-8	alpha	8.2×10^{-17} s	shortest-lived naturally occurring radioisotope
hydrogen-7	neutron emission	2.3×10^{-23} s	shortest-lived artificial isotope known

The half-life, $t_{\frac{1}{2}}$, of a sample of radioactive nuclei is the time taken for exactly half of them to decay.

Figure 3.4.3 compares the decay curves for four different isotopes. The basic shape of the exponential decay curves are the same for each isotope, but the rate of decay is different, indicating different half-lives. Note that after 5 hours there is basically no change in the number of nuclei of cobalt-60, very little fluorine-18, and no nitrogen-13 remaining.

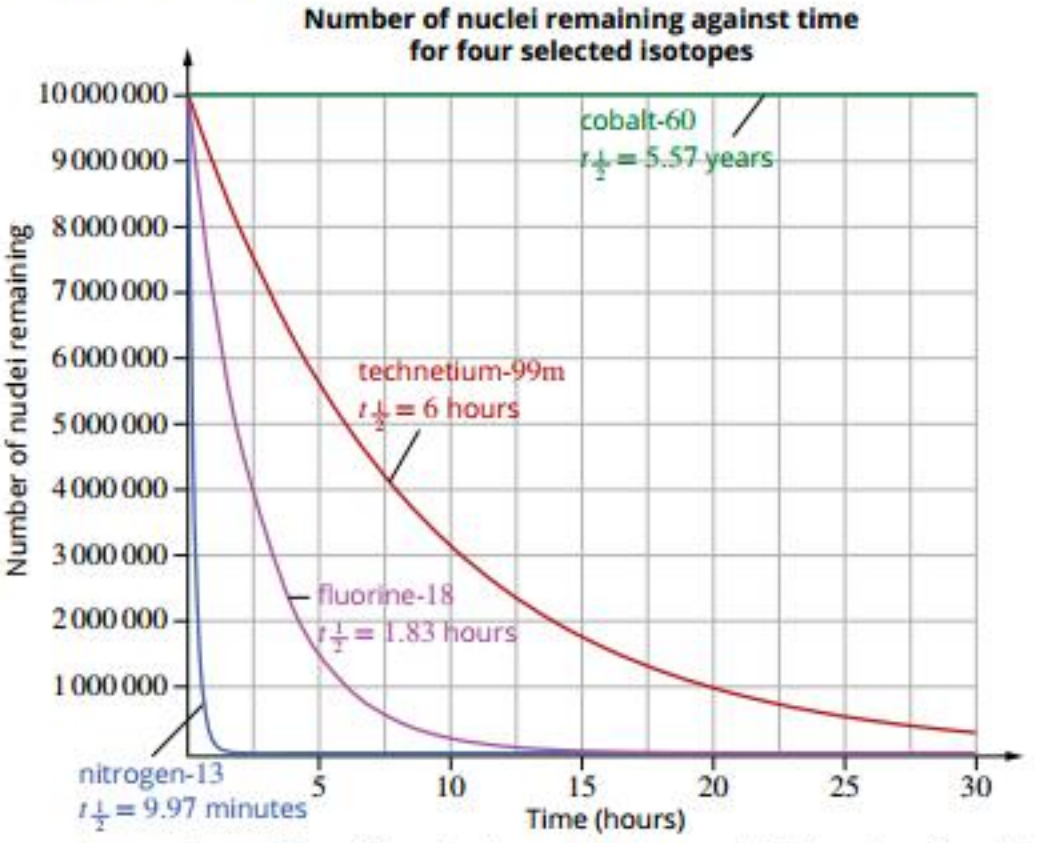


FIGURE 3.4.3 A comparison of four different isotopes with the same initial number of nuclei. The curves show the same exponential shape but have different rates of decay due to the different half-lives of the isotopes. Note that on this scale the Co-60 curve is a straight line. Also, the curves for nitrogen and fluorine do not theoretically touch the x-axis, but at this scale they appear to do so.

Using half-life graphs

Consider the radioisotope einsteinium-242 (Es-242). Its decay curve is shown in Figure 3.4.4. The percentage of Es-242 remaining drops by a factor of 2 each half-life. After one half-life there is only 50% of the nuclei remaining, and after two half-lives there is now only 25% of the nuclei remaining, and so on.

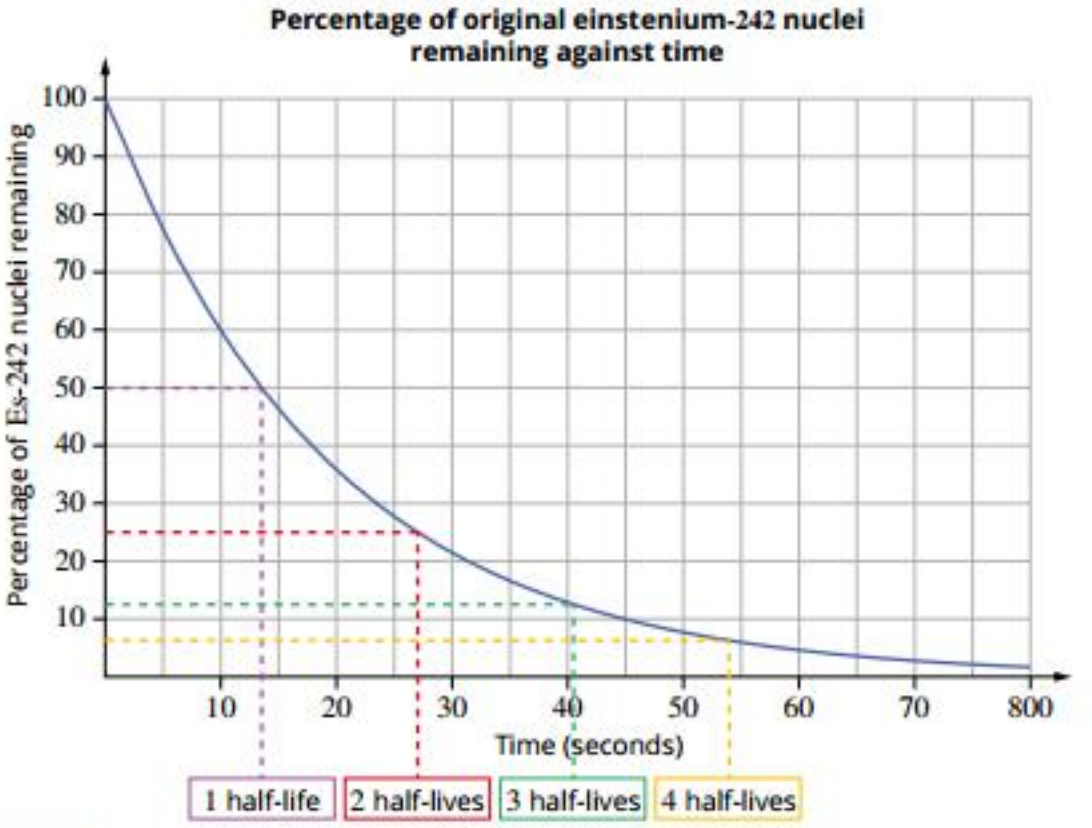


FIGURE 3.4.4 This decay curve of einsteinium-242 shows the percentage of original nuclei remaining against time and after each half-life.

Decay curves can be used to determine the half-life of an isotope by reading when the percentage of nuclei remaining drops to a certain value.

As shown in Figure 3.4.4, after one half-life there will be 50% of the nuclei remaining, and this occurs after about 13.5 seconds. After two half-lives 25% of the nuclei remain, and this occurs after about 27 seconds. Three half-lives take about 40.5 seconds. You expect the time between each half-life to be constant, because the percentage of the number of Es-242 nuclei is reducing by a factor of two each half-life. The time difference between each successive half-life is 13.5 seconds so you can be confident that this is the half-life of einsteinium-242.

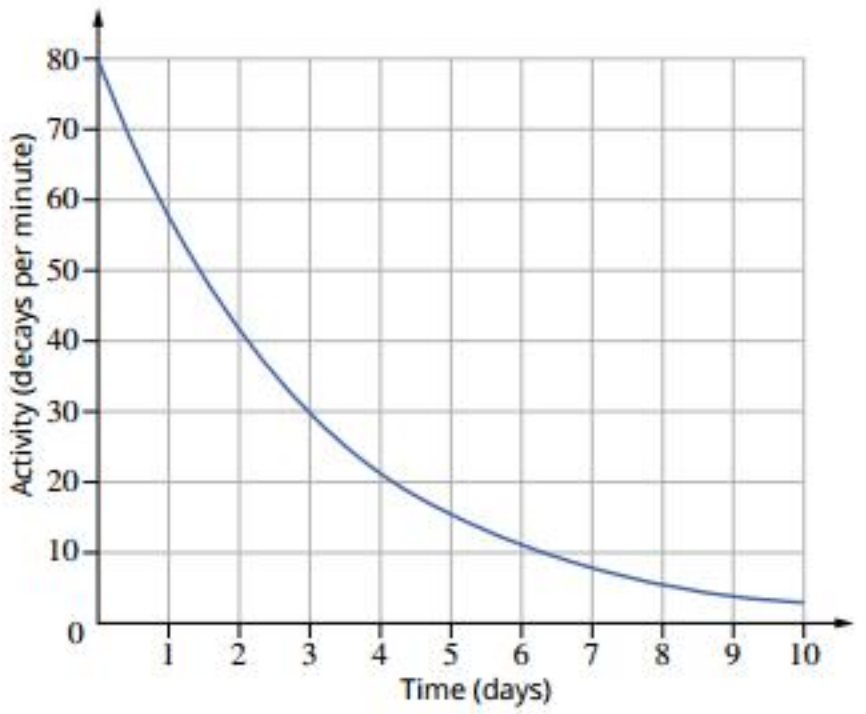
The activity of a sample describes the number of decays per time unit that occur. Activity is sometimes used as a measure of the radioactivity of a sample as it is much easier to determine than the actual number of particles remaining.

A decay curve can be used to determine the half-life of a radioactive sample by reading off the time when exactly 50% of the initial number of nuclei in the sample remains.

Worked example 3.4.1

USING DECAY CURVES

The following graph shows the activity, or number of decays per second, over a period of time for a sample of the radioactive isotope neptunium-238.



Use the graph to answer the following questions:

a Identify the activity of the sample at the start of the measurements.

b Deduce if the activity of the sample ever reaches zero.

c Determine the activity of the sample after 10 days.

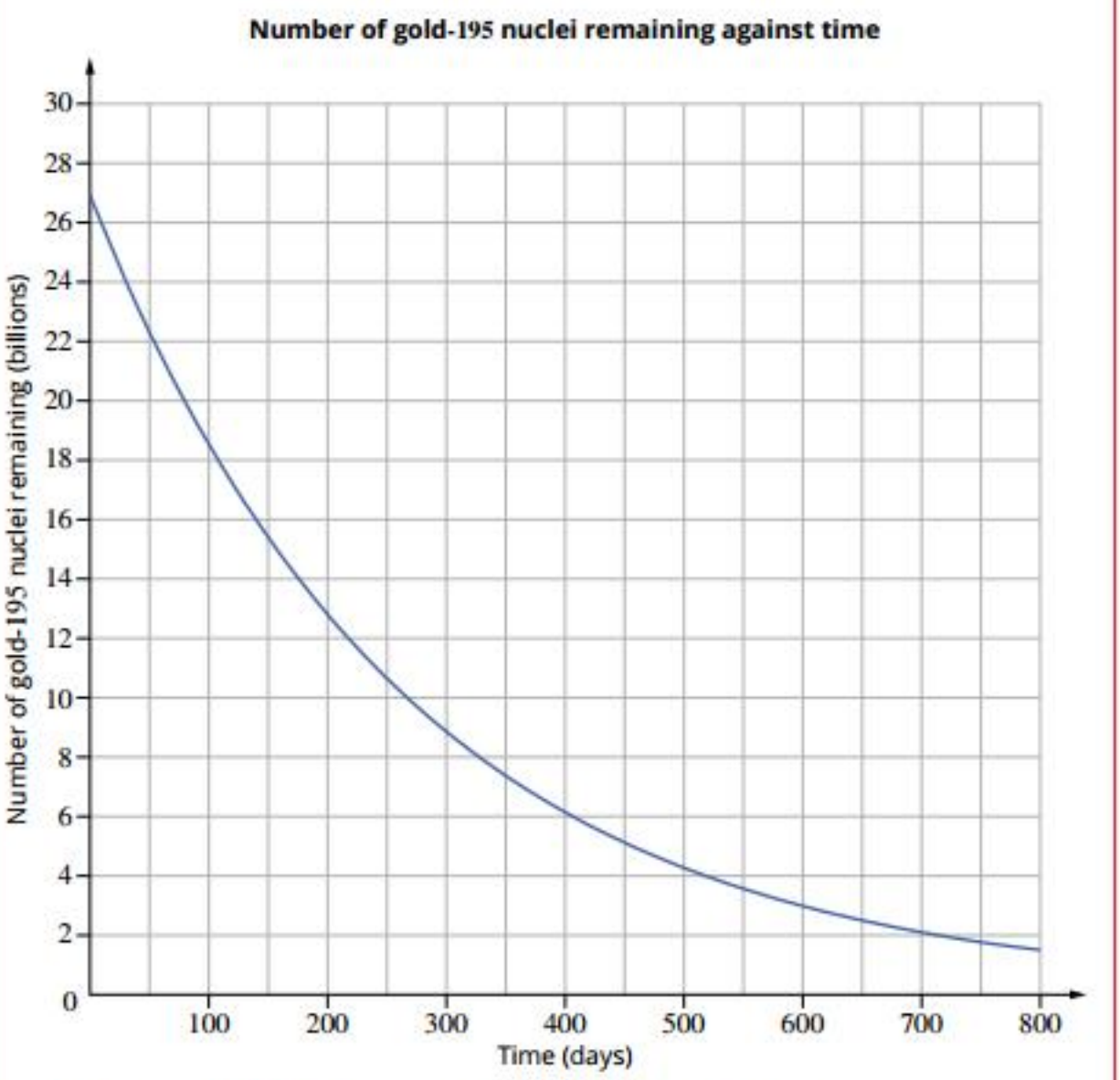
d Determine the half-life of $^{238}_{93}$Np.

Thinking	Working
a The activity at the start of the measurements is when time is zero: *y*-intercept.	When $t = 0$ the count rate is 80 counts per minute.
b Theoretically, an exponential decay curve cannot reach zero, but in radioactive decay the number of nuclei remaining can reach zero when there is one neptunium-238 nucleus left and it decays.	Yes, the activity of the sample can reach zero, because if there is one remaining neptunium-238 nucleus and it decays, then there are exactly zero nuclei left.
c The activity of neptunium-238 after 10 days is read off the *y*-axis when $t = 10$ days.	The activity of neptunium-238 after 10 days is about 3 decays per minute.
d The half-life of neptunium-238 is the time when half the initial number remains. The initial activity is 80 counts per minute, so the time taken to reduce to 40 counts per minute is the half-life.	The half-life of neptunium-238 is approximately 2.1 days.

➤ Try yourself 3.4.1

USING DECAY CURVES

The decay curve of the radioactive isotope gold-195 is shown in the graph below. Use it to answer the following questions.



a Determine the initial number of gold-195 nuclei present.

b Identify when the number of gold-195 nuclei falls to 10% of its initial value.

c Determine the half-life of gold-195.

d Determine the number of nuclei remaining after three half-lives.

Calculations using half-life

If data of nuclei remaining or mass remaining is not available, then you can use a mathematical model of exponential decay to predict how many nuclei remain or the remaining mass after a given time.

The number of nuclei remaining after n half-lives is found by the equation:

$$N = N_0\left(\tfrac{1}{2}\right)^n$$

where

N is the number of radioactive nuclei remaining

N_0 is the initial number of radioactive nuclei

n is the number of half-lives elapsed.

The number of half-lives in a particular time period can be found using:

$$n = \frac{t}{t_{\frac{1}{2}}}$$

where

n is the number of half-lives

t is the period of time over which the radioactive nuclei have decayed

$t_{\frac{1}{2}}$ is the half-life of the radioactive nuclei.

Note that, if the mass of the remaining isotope is known instead of the number of nuclei, then the formula above can be written as:

$$m = m_0\left(\frac{1}{2}\right)^n$$

where

m is the mass of radioactive nuclei remaining (usually measured in g)

m_0 is the initial mass of radioactive nuclei (usually measured in g)

n is the number of half-lives elapsed.

Worked example 3.4.2

CALCULATING NUMBER OF ATOMS REMAINING

A sample of the radioisotope thorium-234 contains 8.0×10^{12} nuclei. The half-life of thorium-234 is 24 days. Calculate how many thorium-234 nuclei will remain in the sample after 100 days.	
Thinking	**Working**
The following information is given: Initial number of nuclei = 8.0×10^{12} Half-life = 24 days Time elapsed = 100 days	$N_0 = 8.0 \times 10^{12}$ $t_{\frac{1}{2}} = 24$ days $t = 100$ $N = ?$
Calculate how many half-lives in 100 days.	$n = \frac{100}{24}$ $= 4.167$ half-lives
Substitute $N_0 = 8.0 \times 10^{12}$ and $n = 4.167$ into the equation $N = N_0\left(\frac{1}{2}\right)^n$. Calculate the number of nuclei remaining.	$N = N_0\left(\frac{1}{2}\right)^n$ $= 8.0 \times 10^{12} \times \left(\frac{1}{2}\right)^{4.167}$ $= 4.5 \times 10^{11}$ nuclei

➤ Try yourself 3.4.2

CALCULATING NUMBER OF ATOMS REMAINING

A sample of the radioisotope sodium-24 contains 4.0×10^{10} nuclei. The half-life of sodium-24 is 15 hours. Calculate the number of sodium-24 atoms remaining in the sample after 82 hours.

Worked example 3.4.3

CALCULATING HALF-LIFE

A 0.1309 kg sample of the radioactive isotope iodine-131 was left in a cupboard for 30.1 days. When the cupboard was opened it was found that only 9.708 g of the isotope remained. Calculate the half-life of this isotope.

Thinking	Working
The following information is given: Initial mass = 0.1309 kg Time elapsed = 30.1 days Remaining mass after 30.1 days = 9.708 g	$m_0 = 0.1309\,\text{kg}$ $t = 30.1$ days $m = 9.708\,\text{g}$ $t_{\frac{1}{2}} = ?$
Convert the units for the mass m to kilograms.	$9.708\,\text{g} = 9.708 \times 10^{-3}\,\text{kg}$
Use the rule for half-life to determine how many half-lives have occurred in the 30.1 days. Maths hint: Logarithms of base 10 are used to determine the value of n here. Logs are taken of both sides. Note that the initial number of atoms and remaining number of atoms could be used in the same rule and 3.753 would also be the number of half-lives.	$m = m_0\left(\frac{1}{2}\right)^n$ $9.708 \times 10^{-3} = 0.1309\left(\frac{1}{2}\right)^n$ $\frac{9.708 \times 10^{-3}}{0.1309} = \left(\frac{1}{2}\right)^n$ $0.07416 = \left(\frac{1}{2}\right)^n$ $\log 0.07416 = \log\left(\frac{1}{2}\right)^n$ $-1.1298 = n\log\left(\frac{1}{2}\right)$ $-1.1298 = n \times -0.30103$ $n = \frac{-1.1298}{-0.30103}$ $n = 3.753$ There have been 3.753 half-lives in the 30.1 days.
The half-life can be found using the half-life rule with the time and number of half-lives.	$n = \frac{t}{t_{\frac{1}{2}}}$ $3.753 = \frac{30.1}{t_{\frac{1}{2}}}$ $t_{\frac{1}{2}} = \frac{30.1}{3.753}$ $= 8.02$ The half-life of iodine-131 is 8.02 days.

➤ Try yourself 3.4.3

CALCULATING HALF-LIFE

An 8.9 g sample of magnesium-28 is weighed on Monday at 12 p.m. If only 0.556 g of magnesium-28 remains on the following Wednesday at 11.36 p.m, determine its half-life in hours.

3.4 Review

SUMMARY

- The rate of decay of a radioisotope is measured by its half-life, $t_{\frac{1}{2}}$. This is the time that it takes for half of the radioisotope to decay.
- The number of atoms of a radioisotope will decrease over time. Over one half-life, the number of atoms of a radioisotope will halve.
- The half-life equation can be used to calculate the number, N, of a radioisotope remaining after a number of half-lives, n, has passed: $N = N_0\left(\frac{1}{2}\right)^n$.
- A graph of the number of radioactive nuclei remaining is an exponential decay curve that decreases at a decreasing rate and can be used to determine the half-life of an isotope.

KEY QUESTIONS

Describe

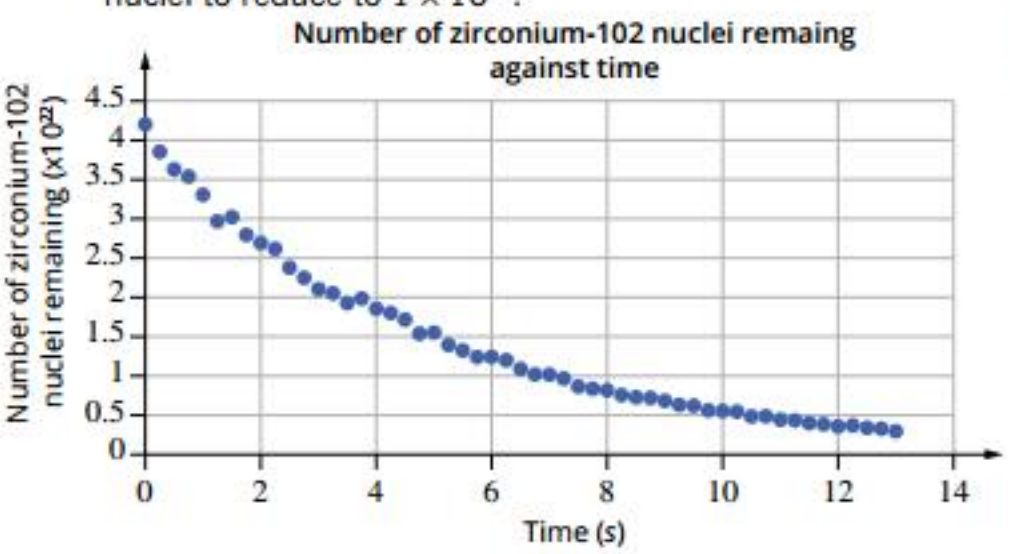
1 If a particular atom in a radioactive sample has not decayed during the previous half-life, determine the chance, as a percentage, that it will decay in the next half-life.

Apply

2 Explain why, after two half-lives, the number of nuclei in a sample of radioactive material has not completely disappeared.

3 The graph shows real data of the number of zirconium-102 nuclei remaining against time. Use it to determine:

- **a** the approximate half-life of the sample
- **b** the number of zirconium-102 nuclei remaining after 10 seconds
- **c** the time taken for the number of zirconium-102 nuclei to reduce to 1×10^{22}.



Analyse

4 Technetium-99m has a half-life of 6.0 hours. A sample of the radioisotope originally contains 8.0×10^{10} atoms. Determine how many technetium-99m nuclei remain after 6.0 hours.

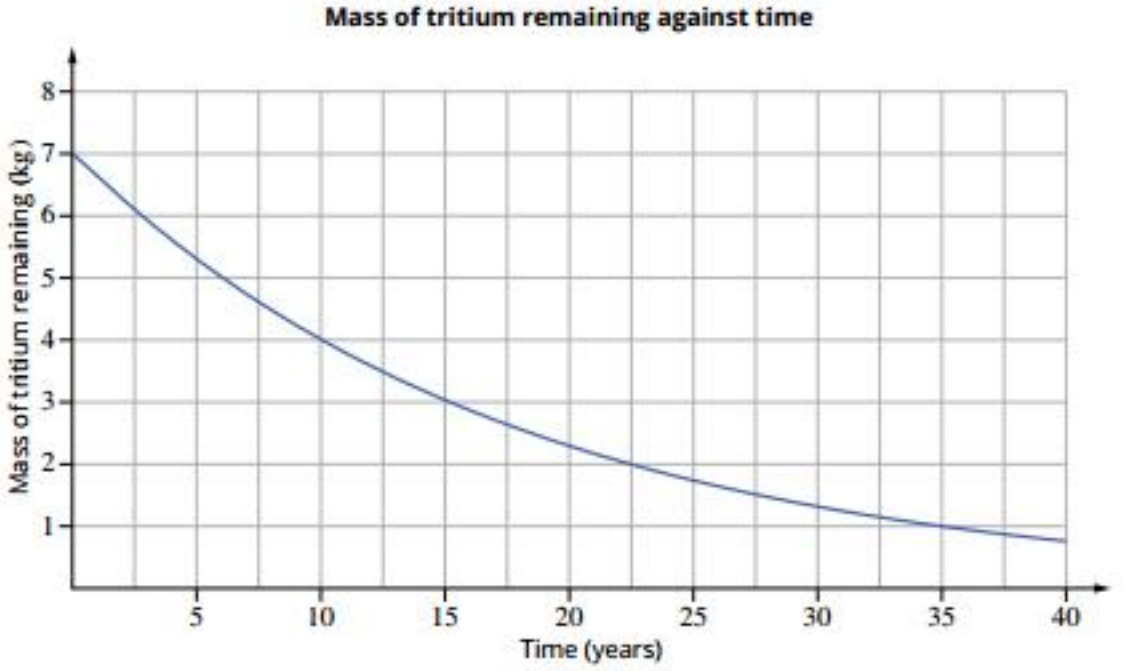
5 A hospital in Alice Springs needs 12 mg of the radioisotope technetium-99m. The specimen must be ordered from Sydney. The half-life of technetium-99m is 6 hours and the delivery takes 24 hours. Calculate how much must be produced in Sydney to satisfy the order for Alice Springs.

6 Radioactive materials are relatively safe when their activity has fallen below 0.1% of the initial value.

- **a** Identify how many half-lives it takes for the activity of a material to fall below this level.
- **b** Plutonium-239 is a by-product of nuclear reactors. Its half-life is 24000 years. Calculate how long the plutonium-239 must be stored as nuclear waste before it is considered safe to handle.

3.4 Review *continued*

7 An amount of tritium (hydrogen-3) is weighed on New Year's Day each year for many years. The results of the experiment are shown in the graph.



Use the graph to answer the following questions:

a How much tritium was present at the start of the observations?

b Determine how much tritium was present after 20 years.

c Determine how long it took the sample of tritium to reduce to 2.0 kg.

d Determine the half-life of tritium.

e Determine how much tritium would remain after 3 half-lives.

f Deduce how much tritium would remain after 5 half-lives.

g Calculate how much tritium would remain after 100 years.

8 The graph shown includes part of the decay curve of sulfur-35. Use the graph to help you answer the following questions.

Sulfur-35 decays via beta negative radiation into the stable isotope chlorine-35.

a Determine how many chlorine-35 nuclei would exist via this decay reaction after 12 days.

b If the half-life of sulfur-35 is 87.5 days, determine how many chlorine-35 nuclei would exist after 262.5 days.

9 A 24 g sample of phosphorus-32 is left in a cupboard over a period of 45 days. If the half-life of P-32 is 14 days, determine how much of the original sample will be remaining after the 45-day period.

3.5 Mass–energy equivalence

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- use the electron volt (eV) as a unit of energy equal to 1.602×10^{-19} J
- recall that an isotope can be intentionally changed into another isotope by bombarding it with another particle in a process called artificial transmutation
- explain that, in any nuclear reaction, the sum of the masses of the reactants will not equal the sum of the masses of the products. This difference is known as the mass defect, Δm
- understand that a nuclear reaction will not proceed naturally if it requires energy; that is, if the mass defect is a negative number
- recall that the energy required to break a nucleus completely into its constituent protons and neutrons is called the binding energy, ΔE
- calculate the binding energy, and binding energy per nucleon, using Einstein's mass–energy equivalence relationship: $\Delta E = \Delta m c^2$
- use the energy equivalence of one atomic mass unit of 931.6 MeV in calculations.

In every instance of radioactive decay, energy is produced as a result of the parent nucleus becoming more stable and creating a daughter nucleus. The amount of energy produced depends on the number of protons and neutrons, and on how tightly they are held together. In this module, you will explore the amount of energy released, not just by natural decay reactions, but also by a whole range of other natural and artificial reactions. It will also be shown that some of the mass of the nucleons is transformed into pure energy using the most famous equation in science: $E = mc^2$.

THE ELECTRON VOLT

The energy released by a single decaying nucleus is very, very small, typically in the order of 2×10^{-11} joules (J). It is time-consuming and inconvenient to write nuclear energies in scientific notation, so physicists use a much smaller unit of energy called the **electron volt**, eV. Note that the electron volt should not be confused with the unit 'volt', which will be used in the electricity chapters that follow.

An electron volt is the amount of work done in moving a single electron through a potential difference (voltage) of 1 volt. You will learn more about this definition in Unit 3. One electron volt (1 eV) is equal to 1.602×10^{-19} J and 1 J is equal to 6.242×10^{18} eV. It is useful to practise converting values between the two units, as described in Table 3.5.1.

TABLE 3.5.1 Converting to and from J and eV

To convert...	Do this	To check
J into eV	Divide the energy in J by 1.602×10^{-19}.	Your number should be much larger than before.
eV to J	Multiply the energy in eV by 1.602×10^{-19}.	Your number should be much smaller than before.

In nuclear physics, most electron energies are described in keV (one thousand, 10^3, eV), MeV (one million, 10^6, eV), GeV (one billion, 10^9, eV) and TeV (one trillion, 10^{12}, eV). Refer to Table 1 on page 518 for the other prefixes.

Note that the eV is not an SI unit, which means that you will need to convert energy in eV to J before making any substitutions into formulas that use SI units.

Table 3.5.2 and Figure 3.5.1 show the comparisons of various energetic processes in joules and in electron volts. This will give you an idea of how small 1 eV is.

TABLE 3.5.2 Energy processes and their equivalent energies

Energy process	Energy in joules	Energy in electron volts	Notes
highest-energy radio waves	2.0×10^{-22}	0.0012 eV (1.2 meV)	the least energetic form of electromagnetic radiation
red light	2.9×10^{-19}	1.8 eV	the lowest-energy light that our eyes can detect
violet light	5.0×10^{-19}	3.1 eV	the highest-energy light that our eyes can detect
typical exothermic chemical reaction such as combustion	1.6×10^{-18}	10 eV	energy released *per reaction*
typical energy per reaction in a nuclear reactor	3.2×10^{-11}	2×10^{8} eV (200 MeV)	this is as a result of nuclear fission reactions usually involving uranium isotopes
a snowflake hitting the ground	1×10^{-6}	6×10^{12} eV (6 TeV)	this is larger than all of the energy received by every radio telescope on Earth
proton collisions in the Large Hadron Collider	1.0×10^{-6}	6.5×10^{12} eV (6.5 TeV)	protons are collided at about 99.999 999% of the speed of light
highest-energy gamma rays	2×10^{-5}	1×10^{14} eV (100 TeV)	the most energetic form of electromagnetic radiation
a falling apple	1	6.2×10^{18} eV (6.2 EeV)	energy attained by an apple falling 1 metre on Earth. 1 EeV (exa electron volt) = 1×10^{18} eV
500 kg car moving at 100 km h^{-1}	200 000	1.2×10^{24} eV (1.2 YeV)	one thousand million million million million times the energy of the lowest energy radio waves 1 YeV (yotta electron volt) = 1×10^{24} eV
most energetic single particle ever observed	50	3.1×10^{20} eV (310 EeV)	a cosmic-ray proton known as the 'Oh My God' particle observed from space in 1991 and thought to have travelled at 99.999 999 999 999 999 999 999 510% of the speed of light; its source remains unknown

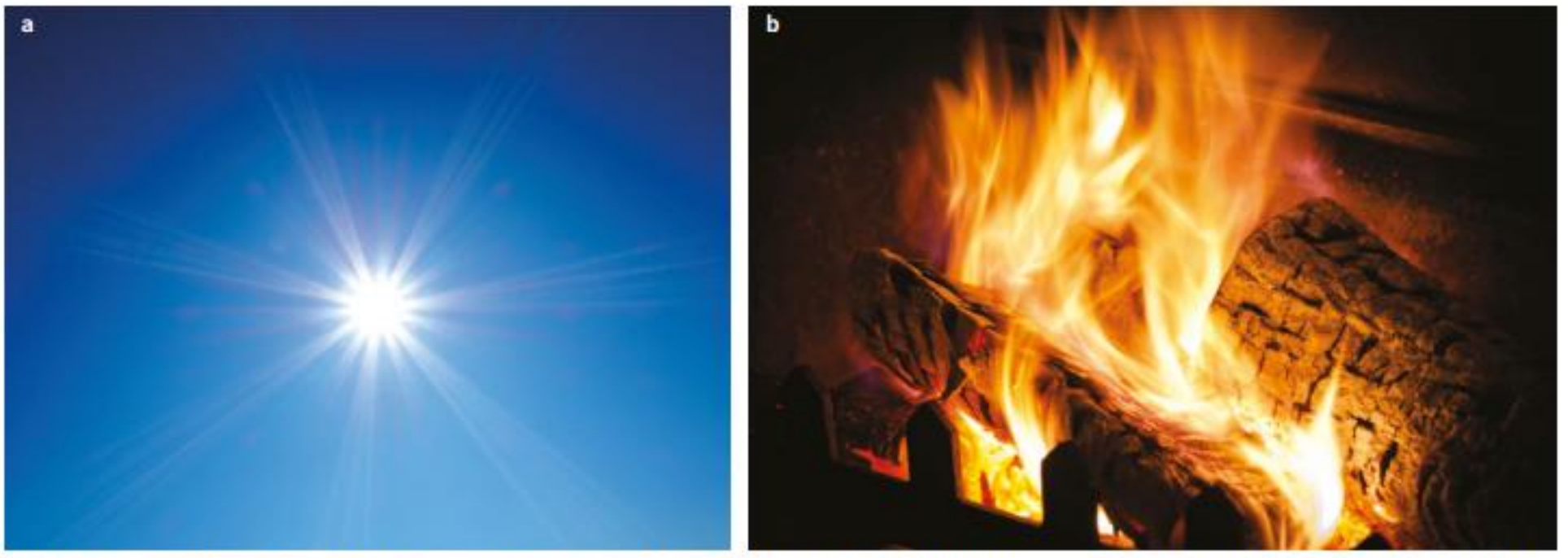


FIGURE 3.5.1 For the same amount of mass used, nuclear reactions occurring inside the Sun (a) produce about 20 million times more energy than that produced by burning wood (b).

Worked example 3.5.1

THE ELECTRON VOLT

Radium-226 is a radioisotope that decays into radon-222 via alpha decay. The reaction is:

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

a In this reaction, 4.934 MeV of energy is released from each radium-226 nucleus. Convert this value to joules.

Thinking	Working
First change 4.934 MeV into eV by multiplying by 10^6, which is the prefix 'mega'.	$4.934\,\text{MeV} = 4.934 \times 10^6\,\text{eV}$
To convert eV into J, multiply by 1.602×10^{-19}.	Energy $= 4.934 \times 10^6 \times 1.602 \times 10^{-19}$ $= 7.904 \times 10^{-13}\,\text{J}$

b If 6.80×10^{24} nuclei of radium-226 nuclei decay, determine the amount of energy that would be released in eV and in joules.

Thinking	Working
Each reaction releases 4.934 MeV of energy. So, 6.80×10^{24} reactions will release $6.80 \times 10^{24} \times 4.934$ MeV of energy.	Total amount of energy $= 6.80 \times 10^{24} \times 4.934 \times 10^6\,\text{eV}$ $= 3.355 \times 10^{31}\,\text{eV}$
Multiply 3.355×10^{31} by 1.602×10^{-19} to find the answer in joules.	Total amount of energy $= 3.355 \times 10^{31} \times 1.602 \times 10^{-19}$ $= 5.375 \times 10^{12}\,\text{J}$

➤ Try yourself 3.5.1

THE ELECTRON VOLT

Radon-222 is a radioisotope that decays into polonium-218 via alpha decay. The reaction is:

$$^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\text{He}$$

a In this reaction, 8.96×10^{-13} J of energy is released from each radon-222 nucleus. Determine how much energy this is in eV and MeV.

b If 5.25×10^{23} nuclei of radon-22 nuclei decay, determine the amount of energy that would be released in eV and in joules.

ARTIFICIAL TRANSMUTATION

In most decay reactions, the daughter nucleus is a different element to the parent nucleus. This is known as transmutation and is a naturally occurring process. Decay is one of the main natural methods by which an element is changed into another element and is the reason why there are elements in the universe that are heavier than iron.

The most common *artificial* reaction in nuclear physics is nuclear bombardment. This involves firing a small particle (proton, neutron, alpha particle etc.) at a nucleus to analyse the particles and nuclei that emerge. The very first artificial nuclear bombardment experiment was carried out by Ernest Rutherford, as shown in Figure 3.5.2. In his famous experiment in 1919, Rutherford bombarded atoms of gaseous nitrogen with alpha particles emitted from a piece of radioactive ore, which led him to find small amounts of oxygen and hydrogen.

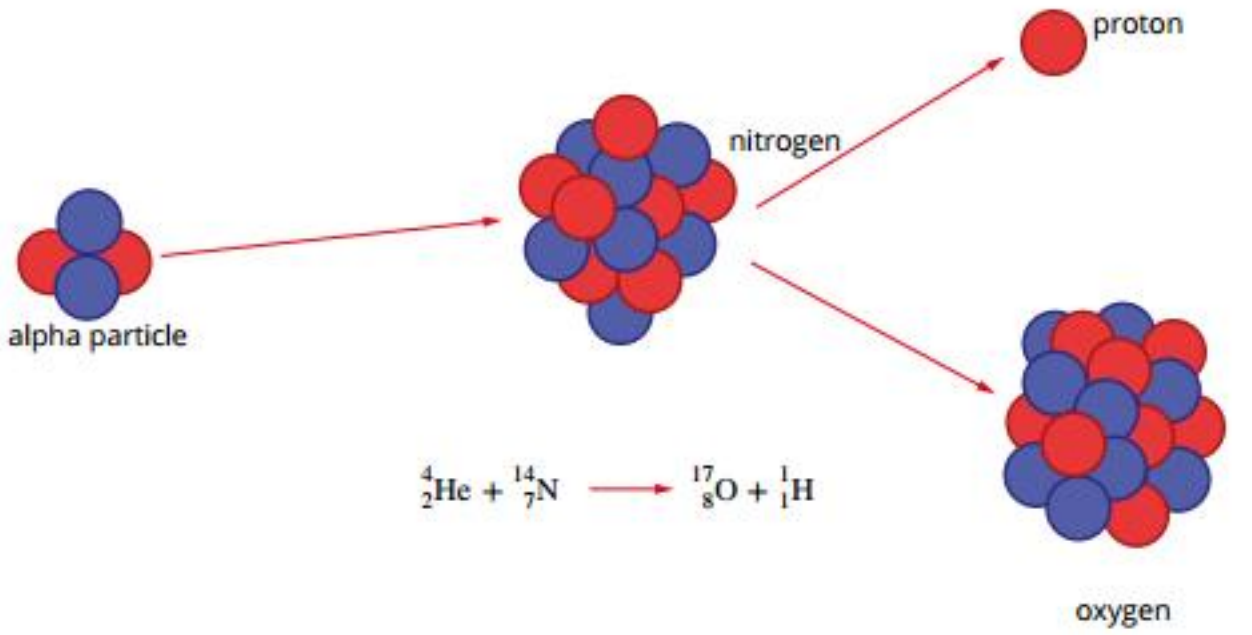


FIGURE 3.5.2 Artificial transmutation of a nitrogen nucleus into an oxygen nucleus and a proton

Rutherford fired an alpha particle at nitrogen-14 (the reactants) and created oxygen-17 with a proton (the products):

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

This was also the first demonstration of a **nuclear reaction**, or transmutation, in which there is *more* than one reactant in the equation. Today, artificial transmutation occurs primarily in nuclear reactors and particle accelerators (Figure 3.5.3). In particle accelerators, increasingly heavier nuclei are fired at each other to try to synthesise heavier and heavier nuclei. An example of this was the creation in 2002 of four atoms of the heaviest element known, oganesson-294, with atomic number 118. In the core of a nuclear reactor, the production of energy via nuclear reactions produces nuclear waste as a by-product. These are typically isotopes of neptunium, americium and curium created by the beta decay of uranium or plutonium when they are bombarded with neutrons.

A nuclear reaction involves two or more particles colliding to produce new particles. It is the main technique of artificial transmutation.

FIGURE 3.5.3 Part of the particle accelerator tunnel at the Joint Institute for Nuclear Research in Dubna, Russia. This facility is responsible for creating the first atoms of nobelium, nihonium, flerovium, moscovium, livermorium, tennessine and oganesson.

Worked example 3.5.2

ARTIFICIAL TRANSMUTATION

The stable isotope cobalt-59 is bombarded with a neutron to produce an unstable isotope that is used in nuclear medicine. The diagram below shows the particles involved in the creation of cobalt-60.

Write the full nuclear equation of this reaction and hence determine the nuclide produced.

Thinking	Working
The reactants of this reaction are cobalt-59 and a neutron, ${}^{1}_{0}n$. There is only one product of this reaction: ${}^{A}_{Z}X$. Cobalt has an atomic number of 27.	${}^{59}_{27}Co + {}^{1}_{0}n \rightarrow {}^{A}_{Z}X$
Mass number and atomic number must be conserved, so A and Z can be calculated.	$A = 59 + 1 = 60$ $Z = 27 + 0 = 27$
Therefore, the nuclide produced is ${}^{60}_{27}Co$ and the complete equation can be written.	${}^{59}_{27}Co + {}^{1}_{0}n \rightarrow {}^{60}_{27}Co$

➤ Try yourself 3.5.2

ARTIFICIAL TRANSMUTATION

The first element heavier than plutonium to be created was curium, which was first made in 1944. The synthesis required the radioisotope plutonium-239 to be bombarded with a smaller particle to produce curium-242 and a single neutron. Identify the smaller particle used for the bombardment reaction and write the full nuclear reaction.

ENERGY IN NUCLEAR REACTIONS

Burning 1 kg of coal typically produces 30 MJ of energy. Burning 1 kg of hydrogen can produce up to 140 MJ of energy, but 'burning' 1 kg of uranium-238 produces 80.6 TJ of energy, or more than 2 million times as much energy as burning coal. Of course, the uranium-238 is not actually burnt as it is in a chemical reaction, but instead it is involved in a nuclear reaction. All nuclear reactions give off millions of times more energy than chemical reactions, but why? The answer lies in the most famous science equation in history, first developed by Albert Einstein (Figure 3.5.4) in 1905.

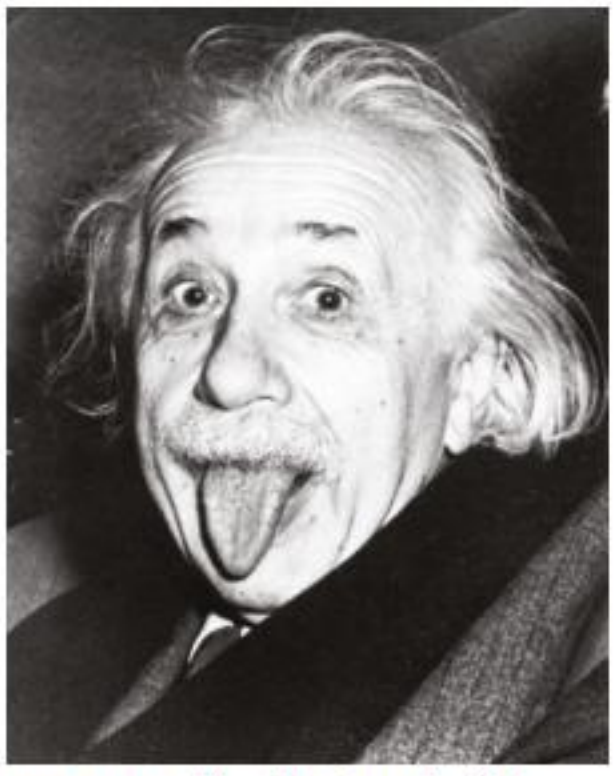


FIGURE 3.5.4 Albert Einstein on his 72nd birthday in 1951

The mass–energy equivalence

Einstein's equation is known as the mass–energy equivalence relationship and governs all energies in nuclear reactions.

$$\Delta E = \Delta mc^2$$

Einstein developed a mathematical rule that linked energy and matter, based on the fact that matter can be converted entirely into energy, and energy can be converted entirely into matter. In a chemical reaction, the atoms are rearranged, and it is the breaking and reforming of the bonds between them that releases energy. In a nuclear reaction, it is the protons and neutrons themselves that are converted *directly* into energy.

Mass is not conserved in all nuclear reactions, which means that the sum of the masses of the reactants does not equal the sum of the masses of the products. This might seem to violate conservation laws, but because the missing mass has been converted into energy, the law of conservation of energy still applies.

The mass–energy equivalence relationship:

$\Delta E = \Delta mc^2$

where

ΔE is the energy content produced in a nuclear reaction (J)

Δm is the difference in mass before and after a nuclear reaction has taken place (kg)

c is the speed of light $2.99792 \times 10^8\,\text{m s}^{-1}$, shortened to $3.00 \times 10^8\,\text{m s}^{-1}$.

Worked example 3.5.3

THE MASS–ENERGY EQUIVALENCE

Determine how much energy, in J and MeV, is released if 5.00×10^{-28} kg of matter is converted into energy.

Thinking	Working
This is a direct application of Einstein's energy–mass equivalence rule: $\Delta E = \Delta mc^2$	$\Delta m = 5.00 \times 10^{-28}\,\text{kg}$ $c = 2.99792 \times 10^8\,\text{m s}^{-1}$
Substitute in for Δm and c to find the energy in joules (using kg for Δm).	$\Delta E = \Delta mc^2$ $= 5.00 \times 10^{-28} \times (2.99792 \times 10^8)^2$ $= 4.49 \times 10^{-11}\,\text{J}$
Convert to eV by dividing by 1.602×10^{-19}.	$= 2.81 \times 10^8\,\text{eV}$
Convert to MeV by dividing by 10^6.	$= 281\,\text{MeV}$

➤ Try yourself 3.5.3

THE MASS–ENERGY EQUIVALENCE

The nuclear bomb dropped on Hiroshima in 1945 converted a 'mere' 0.6 g of uranium into energy. Calculate the amount of energy, in J, that was released in that explosion.

The unified atomic mass unit

The masses of protons and neutrons are very small, so the continual use of kilograms becomes inconvenient (as with the energy unit, joule). Physicists and chemists have, therefore, come up with a more convenient unit of expressing particle masses. This is known as the unified atomic mass unit (u). One unified atomic mass unit (1 u) is defined as $\frac{1}{12}$ of the mass of a carbon-12 atom (6 protons, 6 neutrons and 6 electrons), which is $1.660\,54 \times 10^{-27}$ kg. Figure 3.5.5 and Table 3.5.3 outline how to convert between u and kg.

The atomic mass unit, u, is the unit of mass in which nucleons and nuclei are measured.

$1\,\text{u} = 1.660\,54 \times 10^{-27}\,\text{kg}$

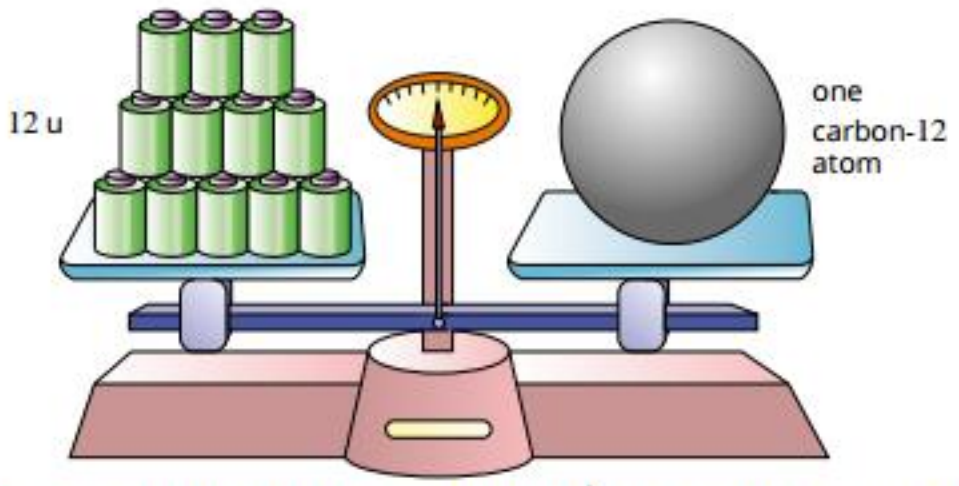


FIGURE 3.5.5 The atomic mass unit (u) is exactly equal to $\frac{1}{12}$ the mass of a carbon-12 atom.

TABLE 3.5.3 Converting to and from kg and u

To convert...	Do this	To check
kg into u	Divide the mass in kg by 1.66054×10^{-27}.	Your number should be much larger than before.
u to kg	Multiply the mass in u by 1.66054×10^{-27}.	Your number should be much smaller than before.

Using this conversion factor, Table 3.5.4 lists some particles and isotopes and their masses. Note that the mass of the isotopes given includes their orbiting electrons, which is why hydrogen-1 has a slightly heavier mass than a proton. Orbiting electrons do not participate in any common nuclear reactions, so they will not form part of the Δm value in the mass–energy rule. When Δm is calculated in a nuclear reaction, the masses of the orbiting electrons will cancel out.

TABLE 3.5.4 Selected particles and isotopes and their masses in kg and u

Particle or isotope	Mass in kg	Mass in u
electron and positron	9.109384×10^{-31}	0.0005486
proton	1.672622×10^{-27}	1.007276
hydrogen-1	1.673534×10^{-27}	1.007825
neutron	1.674927×10^{-27}	1.008665
alpha particle (*nucleus* of helium-4)	6.644661×10^{-27}	4.001506
carbon-12	$1.9926 5 \times 10^{-27}$	12 exactly
uranium-238	3.952929×10^{-25}	238.0507882

The masses of all particles and isotopes are known to a very high precision, so many significant figures can be written during calculations. Therefore, it is important to keep track of as many significant figures as possible. It is also valuable to know how much energy is released if exactly 1 u is converted into energy. Using the mass–energy rule for 1 u:

$$\begin{aligned}\Delta E &= \Delta m c^2 \\ &= 1\,\text{u} \times (2.99792 \times 10^8)^2 \\ &= 1.66054 \times 10^{-27} \times 8.98752 \times 10^{16} \\ &= 1.49241 \times 10^{-10}\,\text{J} \\ &= \frac{1.49241 \times 10^{-10}}{1.602 \times 10^{-19}} = 9.3159 \times 10^8\,\text{eV} \\ &= 931.6\,\text{MeV}\end{aligned}$$

This means that 1 u of matter is equivalent to 931.6 MeV of energy.

> 1 u of mass has an energy equivalent of 931.6 MeV.

This relationship offers a helpful short-cut to performing energy calculations using the mass–energy rule. Simply calculate the change in mass of the reaction (u) and multiply it by 931.6 MeV to find the energy released. For example, from Table 3.5.4, an electron has a mass of $9.109\,384 \times 10^{-31}$ kg or 0.000 548 6 u.

$$\begin{aligned}\Delta E &= \text{mass in u} \times 931.6 \\ &= 5.486 \times 10^{-4} \times 931.6 \\ &= 0.5111\ \text{MeV}\end{aligned}$$

An electron has an energy equivalence of 0.511 MeV.

Worked example 3.5.4

THE UNIFIED ATOMIC MASS UNIT

Calculate the amount of energy (in MeV) that would be released if the nucleus of the iron-52 radioisotope were to be completely converted into energy. The mass of the iron-52 isotope is 51.9484 u.	
Thinking	**Working**
The isotopic mass of iron-52 is given, which includes the mass of the electrons. The mass of an electron is 0.000 548 6 u.	Isotopic mass = 51.9484 u
Iron has an atomic number of 26, so the mass of 26 electrons needs to be subtracted from the isotopic mass to get the nuclear mass in u. Mass of nucleus = mass of isotope – mass of 26 electrons	Mass of nucleus = 51.9484 – 26 × 0.000 548 6 = 51.9484 – 0.0142636 = 51.9341 u
If this mass is completely converted into energy, 931.6 MeV is produced for each u of mass, therefore the amount of energy released is the nuclear mass multiplied by 931.6.	Energy released = mass of nucleus × 931.6 MeV = 51.9341 × 931.6 = 48380 MeV

➤ Try yourself 3.5.4

THE UNIFIED ATOMIC MASS UNIT

Calculate the amount of energy (in MeV) that would be released if the nucleus of the lithium-5 radioisotope (m = 5.012 54 u) were to be completely converted into energy.

Mass defect and binding energy

If the products of a nuclear reaction are weighed accurately and compared with the mass of the reactants, then there is always a difference. Some mass is lost during the nuclear reaction, and that lost mass is converted into energy.

If a given, intact nucleus could be disassembled into its individual protons and neutrons, then the sum of the masses of the individual protons and neutrons would be slightly higher than the mass of the nucleus itself. The difference between the mass of the nucleus as a whole and the sum of the individual nucleons is called the **mass defect**, Δm. The energy equivalent of the mass defect is called the **binding energy**, ΔE, and is the work or energy needed to break apart a given nucleus into its individual parts. Another way of describing this is that some of the mass of the individual protons and neutrons that make up the nucleus is converted into energy that keeps the nucleus together when it is formed. Therefore, you can say that to construct a nucleus releases energy, and to fully break apart a nucleus requires energy.

The mass defect is the difference between the mass of the intact nucleus and the sum of the masses of the individual nucleons that make up the nucleus.

The binding energy is how much energy is needed to completely break up an intact nucleus into its individual protons and neutrons.

When dealing with nuclear equations, it is more practical to calculate the mass defect (in u) as:

$$\Delta m = \text{total mass of reactants} - \text{total mass of products}$$

or

$$\Delta m = \text{mass of nucleus} - \text{total mass of individual protons and neutrons}$$

In terms of binding energy, the general equation is:

$$\text{mass of nucleus} + \text{binding energy} \rightarrow \text{total mass of individual protons} + \text{total mass of individual neutrons}$$

Binding energy is shown diagrammatically in Figure 3.5.6.

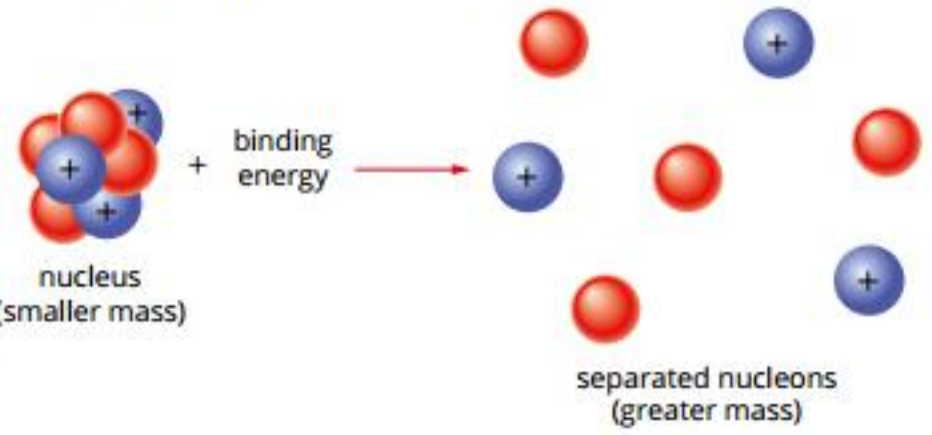


FIGURE 3.5.6 Energy, called the binding energy, must be supplied to a nucleus to completely separate its individual protons and neutrons.

The binding energy is calculated using the conversion factor of 931.6 MeV per u:

$$\Delta E = 931.6 \times \Delta m$$

For example, the mass defect and binding energy of the isotope fluorine-19 can be calculated as follows.

Fluorine-19 has a nuclear mass of 18.993 465 82 u (and is the only stable isotope of fluorine).

Fluorine has an atomic number of 9 and a mass number of 19, so there are 10 neutrons in its nucleus.

Remember from Table 3.5.4 that proton mass is 1.007 276 u and neutron mass is 1.008 665 u.

The nuclear reaction to completely break apart fluorine-19 into its 9 protons and 10 neutrons is:

$$^{19}_{9}\text{F} \rightarrow 9\ ^{1}_{1}\text{H} + 10\ ^{1}_{0}\text{n}$$

The mass defect of fluorine-19 is therefore:

$$\begin{aligned}\Delta m &= \text{mass of fluorine-19 nucleus} - (\text{mass of 9 protons} + \text{mass of 10 neutrons}) \\ &= 18.993\,465\,82 - (9 \times 1.007\,276 + 10 \times 1.008\,665) \\ &= 18.993\,465\,82 - (9.065\,484 + 10.086\,65) \\ &= 18.993\,465\,82 - 19.152\,134 \\ &= -0.158\,668\,18\ \text{u}\end{aligned}$$

The negative result indicates that the sum of the masses of the individual 19 nucleons is greater than the mass of the fluorine-19 nucleus, as illustrated in Figure 3.5.7 on page 92.

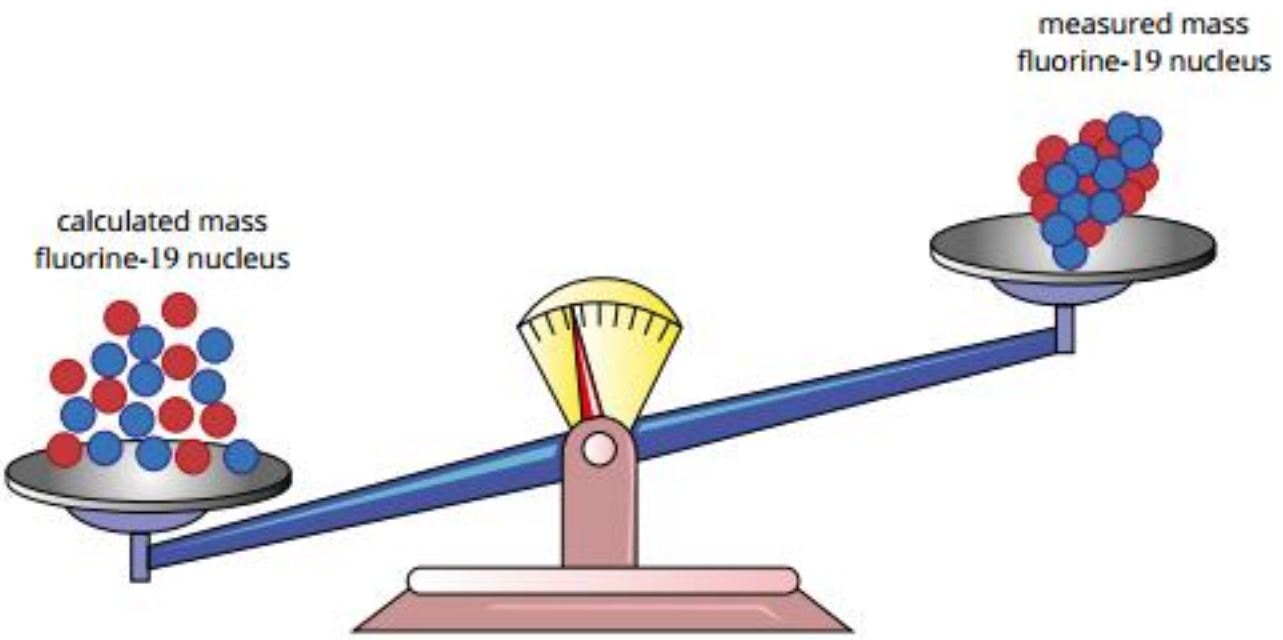


FIGURE 3.5.7 The sum of the masses of the 9 protons and 10 neutrons is larger than the mass of the fluorine-19 nucleus, indicating that mass has been converted into binding energy.

Note that the negative sign indicates that energy must be supplied for this reaction to occur, and so will not proceed naturally. The binding energy required to disassemble the fluorine-19 nucleus, ignoring the negative sign for the binding energy, is therefore:

$$\Delta E = 931.6 \times 0.158\,66818$$

$$= 147.8\,\text{MeV}$$

This means that 147.8 MeV of energy is needed to break apart the fluorine-19 nucleus into 9 protons and 10 neutrons. You can now write the complete nuclear reaction of the disassembly of fluorine-19 into its individual protons and neutrons:

$$^{19}_{9}\text{F} \rightarrow 9\,^{1}_{1}\text{H} + 10\,^{1}_{0}\text{n}$$

As the number of nucleons in a nucleus increases, so does the nuclear mass of the nucleus, and the binding energy of the nucleus. In order to compare the binding energies of nuclei, the binding energy is divided by the mass number. This is known as the **binding energy per nucleon** and it is an indication of how strongly a nucleus is held together. Nuclei with high binding energies per nucleon are held more tightly than nuclei with lower binding energies per nucleon because it takes more energy to completely separate them.

The binding energy per nucleon for fluorine-19 is:

$$\Delta E = \frac{147.8}{19}$$

$$= 7.779\,\text{MeV per nucleon}$$

Most stable isotopes have a binding energy per nucleon of about 8 MeV per nucleon.

The binding energy per nucleon is equal to the binding energy of a nucleus divided by the number of nucleons in the nucleus. It can be used to determine the stability of a nucleus.

Worked example 3.5.5

BINDING ENERGY PER NUCLEON

Calculate the binding energy per nucleon of the isotope nickel-62. Its nuclear mass is 61.91299 u. Comment on the stability of this isotope.	
Thinking	**Working**
Identify the type and number of nucleons in nickel-62. Write the nuclear reaction for the total break-up of a nickel-62 nucleus into its parts.	Atomic number of nickel-62 is 28. Mass number of nickel-62 is 62. Neutron number of nickel-62 is 62 – 28 = 34 $^{62}_{28}\text{Ni} \rightarrow 28\ ^{1}_{1}\text{H} + 34\ ^{1}_{0}\text{n}$
The mass defect is the mass of the nucleus minus the mass of the 28 protons and the mass of the 34 neutrons. From Table 3.5.4, proton mass is 1.007 276 u and neutron mass is 1.008 665 u.	$\Delta m = 61.91299 - (28 \times 1.007276 + 34 \times 1.008665)$ $= 61.91299 - (28.203728 + 34.29461)$ $= 61.91299 - 62.498338$ $= -0.585348$ u The negative mass indicates that this reaction will not proceed naturally.
The binding energy equivalent of the mass defect is found by multiplying the mass defect by 931.6 MeV per u.	$\Delta E = 0.585348 \times 931.6$ $= 545.3$ MeV
To find the binding energy per nucleon, divide by 62 (mass number).	ΔE per nucleon = 8.795 MeV per nucleon
Stable nuclei have a binding energy per nucleon of about 8.	Therefore, nickel-62 is a very stable isotope because its binding energy per nucleon is more than 8 MeV per nucleon.

➤ Try yourself 3.5.5

BINDING ENERGY PER NUCLEON

Calculate the binding energy per nucleon of the radioisotope uranium-235. Its nuclear mass is 234.993 51 u.

ENERGY IN DECAY

Einstein's mass–energy equivalence relationship can also be used to determine how much energy is released in natural radioactive decay. In any decay reaction, the sum of the masses of the products (daughter nuclei and other particles) will be lower than the mass of the reactants (the parent nucleus). This difference in mass will therefore be equivalent to the energy released by the decay process.

Alpha decay energy

In alpha decay, the mass difference, and therefore the energy released, will be given by:

mass difference in alpha decay = mass of parent nucleus – mass of daughter nucleus – mass of $^{4}_{2}\text{He}$

energy released = mass difference × 931.6Mev

Note that the masses of the isotopes can be used instead of the masses of the nuclei because the masses of the electrons are the same on each side of the equation and so will simply cancel out. The mass of helium-4 (alpha particle and two electrons) is 4.002 604 u.

i The energy released in any alpha decay reaction is equal to:

$\text{Energy} = (m_{\text{parent isotope}} - m_{\text{daughter isotope}} - 4.002604) \times 931.6\ \text{MeV}$

Worked example 3.5.6

ALPHA DECAY ENERGY

Radium-226 was once used in paint on the dials of watches and clocks in the first half of the 20th century. It decays via alpha radiation with a visible glow when ultraviolet light is shone onto it. The hands of this clock from the 1950s glow brightly under UV light because the radium used in the paint gives off alpha radiation.

Write the decay equation for this process and use it to determine how much energy is released.

The isotopic masses of each particle in this decay reaction are:

Mass of radium-226 = 226.025 4 u

Mass of helium-4 = 4.002 604 u

Mass of daughter isotope = 222.017 5 u

Thinking	Working
This is an alpha decay reaction, so there will be an alpha particle, $^{4}_{2}\text{He}$, emitted, and a daughter nucleus, $^{A}_{Z}\text{X}$. Note that the isotopic masses are used here rather than the nuclear masses, because the number of electrons on each side of the reaction balances.	$^{226}_{88}\text{Ra} \rightarrow {}^{4}_{2}\text{He} + {}^{A}_{Z}\text{X}$
To find $^{A}_{Z}\text{X}$, use the conservation of mass number and conservation of atomic number.	$226 = 4 + A$, so $A = 226 - 4 = 222$ $88 = 2 + Z$, so $Z = 88 - 2 = 86$
The daughter nuclei have an atomic number of 86, which is radon. Write the full alpha decay reaction.	$^{226}_{88}\text{Ra} \rightarrow {}^{4}_{2}\text{He} + {}^{222}_{86}\text{Rn}$
To find the energy given off by the alpha radiation, calculate the difference in mass between the reactants and products.	Δm = mass of $^{226}_{88}\text{Ra}$ – mass of $^{226}_{86}\text{Rn}$ – mass of $^{4}_{2}\text{He}$ = 226.025 4 – 222.017 5 – 4.002 604 = 0.005 296 u Note that this reaction will proceed naturally because the mass difference is a positive number.
Therefore, the energy released by the alpha decay is the mass difference multiplied by 931.6 MeV per u.	Energy released = 0.005 296 × 931.6 = 4.934 MeV

➤ Try yourself 3.5.6

ALPHA DECAY ENERGY

Write the nuclear equation for the alpha decay of uranium-238 and use it to determine how much energy is released.

The isotopic masses of each particle in this decay reaction are:

Mass of uranium-238 = 238.050 788 2 u

Mass of helium-4 = 4.002 604 u

Mass of daughter isotope = 234.043 596 u

Beta decay energies

The energy released in beta decay reactions is about ten times less than the energy released in alpha decay reactions.

In beta negative decay, a neutron changes into a proton and an electron is emitted from the nucleus. This means the atomic number of the daughter isotope is one greater than that of the parent isotope, and the daughter isotope will have one more electron than the parent isotope. The mass of this extra electron balances the mass of the electron lost as beta decay, so it is not necessary to include the mass of the electron in the calculation (as you do for an alpha particle). The mass difference is just the difference between the parent and daughter isotope masses (rather than nuclear masses):

Mass difference in beta negative decay = mass of parent isotope – mass of daughter isotope

Energy released = mass difference × 931.6MeV

This is because the mass of the electron produced in the decay is already accounted for in the masses of the parent and daughter isotopes.

The energy released in any beta negative decay reaction is equal to:

$$\text{energy} = (m_{\text{parent isotope}} - m_{\text{daughter isotope}}) \times 931.6\,\text{MeV}$$

Worked example 3.5.7

BETA NEGATIVE DECAY ENERGY

Thallium-204 decays via beta negative radiation. Write the decay equation for this process and use it to determine how much energy is released.

The isotopic masses of each particle in this decay reaction are:

Mass of thallium-204 = 203.9738635u

Mass of electron = 0.0005486u

Mass of daughter isotope = 203.9730436u

Mass of antineutrino = 0u

Thinking	Working
This is a beta negative decay reaction, so there will be an electron, $^{0}_{-1}\beta$, and an antineutrino, $^{0}_{0}\bar{\nu}$, emitted, with a daughter nucleus, $^{A}_{Z}X$, remaining.	$^{204}_{81}Tl \rightarrow {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}_e + {}^{A}_{Z}X$
To find $^{A}_{Z}X$, use the conservation of mass number and conservation of atomic number.	$204 = 0 + 0 + A$, so $A = 204$ $81 = -1 + 0 + Z$, so $Z = 81 + 1 = 82$
The daughter nuclei have an atomic number of 82, which is lead. Write the full beta negative decay reaction.	$^{204}_{81}Tl \rightarrow {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}_e + {}^{204}_{82}Pb$
To find the energy given off by the beta negative decay, the difference in mass between the parent and daughter isotopes only is needed. The mass of the electron is *not* needed in this type of decay calculation. The mass of the neutrino is virtually zero, so this particle does not contribute to the mass difference.	Δm = mass of $^{204}_{81}Tl$ – mass of $^{204}_{82}Pb$ = 203.9738635 – 203.9730436 = 0.0008199u Note that this reaction will proceed naturally because the mass difference is a positive number.
Therefore, the energy released by the beta negative decay is the mass difference multiplied by 931.6MeV per u.	Energy released = 0.0008199 × 931.6 = 0.7638MeV

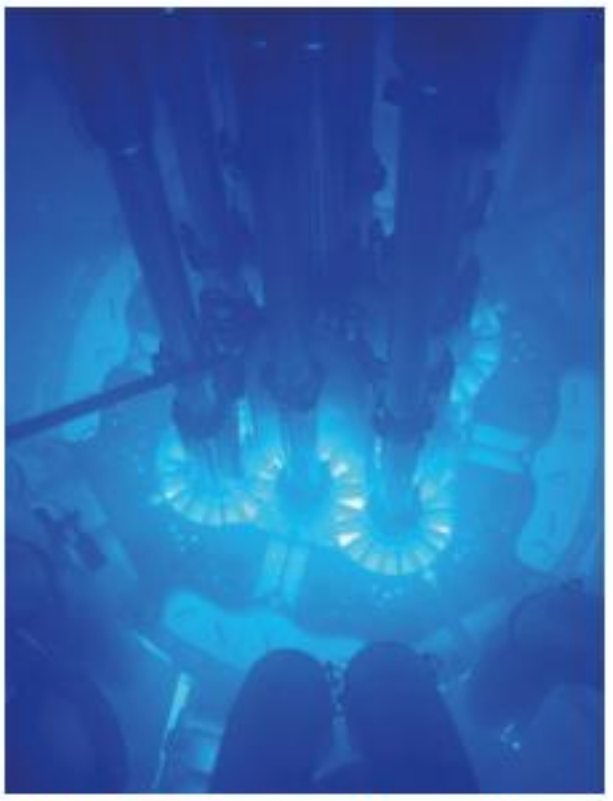


FIGURE 3.5.8 The blue 'Cerenkov radiation' glow around this submerged nuclear reactor core is due to beta decay particles travelling faster than the speed of light in water.

➤ Try yourself 3.5.7

BETA NEGATIVE DECAY ENERGY

Write the nuclear equation for the beta negative decay of tritium (hydrogen-3) and use it to determine how much energy is released per reaction.

The isotopic masses of each particle in this decay reaction are:

Mass of hydrogen-3 = 3.016049279 u

Mass of daughter isotope = 3.0160293 u

The situation is different in beta positive decay because a positron is produced, rather than an electron. Positrons do not make up ordinary matter and are therefore not accounted for in the isotope masses. The daughter isotope has one proton fewer than the parent nucleus, so the daughter isotope will also have one electron fewer than the parent isotope. To find the mass difference, you must subtract the mass of the daughter isotope, as well as *twice* the mass of an electron, from the parent isotope. This extra mass difference comes from the mass of the positron and the one fewer electron in the daughter isotope.

mass difference in beta positive decay = mass of parent isotope − mass of daughter isotope − 2 × mass of electron

energy released = mass difference × 931.6 MeV

The energy released in any beta positive decay reaction is equal to:

$$\text{energy} = (m_{\text{parent isotope}} - m_{\text{daughter isotope}} - 0.0010972) \times 931.6\,\text{MeV}$$

The energy given off during any beta decay reaction is most commonly seen as an eerie blue glow around the core of a nuclear reactor (Figure 3.5.8). This is known as Cerenkov radiation, and results when the electrons or positrons produced travel faster than the speed of light in the water medium surrounding the reactor.

Worked example 3.5.8

BETA POSITIVE DECAY ENERGY

Fluorine-18 decays via beta positive radiation and is used extensively in positron emission tomography (PET) scans. Write the decay equation for this process and use it to determine how much energy is released.

The isotopic masses of each particle in this decay reaction are:
Mass of fluorine-18 = 18.0009380 u
Mass of positron = 0.0005486 u
Mass of daughter isotope = 17.9991610 u
Mass of neutrino = 0 u

Thinking	Working
This is a beta positive decay reaction, so there will be a positron, ${}^{0}_{1}\beta$, and a neutrino, ${}^{0}_{0}\nu_e$, emitted, with a daughter nucleus, ${}^{A}_{Z}X$, remaining.	${}^{18}_{9}F \rightarrow {}^{0}_{1}\beta + {}^{0}_{0}\nu_e + {}^{A}_{Z}X$
To find ${}^{A}_{Z}X$, use the conservation of mass number and conservation of atomic number.	$18 = 0 + 0 + A$, so $A = 18$ $9 = 1 + 0 + Z$, so $Z = 9 - 1 = 8$
The daughter nuclei have an atomic number of 8, which is oxygen. Write the full beta positive decay reaction.	${}^{18}_{9}F \rightarrow {}^{0}_{1}\beta + {}^{0}_{0}\nu_e + {}^{18}_{8}O$

To find the energy given off by the beta positive decay, the difference in mass is needed. This is found by subtracting the mass of oxygen-18 and two positrons from the mass of the fluorine-18 isotope. This is because oxygen-18 has one fewer electrons (same mass as the positron) than fluorine-18, and the positron created also takes away some mass from the fluorine-18 nucleus. The mass of the neutrino is virtually zero, so this particle contributes nothing to the mass difference.	Δm = mass of $^{18}_{9}F$ – mass of $^{18}_{8}O$ – 2 × mass of $^{0}_{-1}\beta$ = 18.0009380 – 17.9991610 – 2 × 0.0005486 = 0.0006798 u Note that this reaction will proceed naturally because the mass difference is a positive number.
Therefore the energy released by the beta positive decay is the mass difference multiplied by 931.6 MeV per u.	Energy released = 0.00006798 × 931.6 = 0.6333 MeV or 633.3 keV

➤ Try yourself 3.5.8

BETA POSITIVE DECAY ENERGY

Write the nuclear equation for the beta positive decay of mercury-189 and use it to determine how much energy is released per reaction.

Isotopic masses needed are:

Mass of mercury-189 = 188.96819 u

Mass of positron = 0.0005486 u

Mass of daughter isotope = 188.963948 u

Gamma decay energy

There is no change in the mass number, atomic number or actual mass of the nucleus undergoing gamma decay, so there will be no mass difference between the parent and daughter nuclei. The parent nucleus loses energy because it is in a higher 'state' of energy. This is similar to an object on a high shelf having a higher 'state' of energy than an object on a lower shelf. When the parent nucleus falls to a lower 'state' it gives off energy as a gamma ray, as the nucleus reorganises its nucleons to a more stable arrangement. Gamma decay usually occurs after beta or alpha decay because those processes physically change the mass or the number of nucleons in the parent nucleus, leaving the daughter nucleus with an unstable arrangement of nucleons.

The gamma decay reaction for technetium-99m (also called *metastable* technetium-99) releases 140 keV of energy and is written as:

$$^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc + ^{0}_{0}\gamma$$

The technetium-99 nucleus reorganises itself into a more stable configuration after the 140 keV gamma ray has been emitted, and it has the same atomic and mass numbers as the technetium-99m nucleus.

THE BINDING ENERGY PER NUCLEON CURVE

The higher the binding energy per nucleon of a nucleus, the more stable the nucleus is. Figure 3.5.9 is a graph of binding energy per nucleon against mass number for every known isotope.

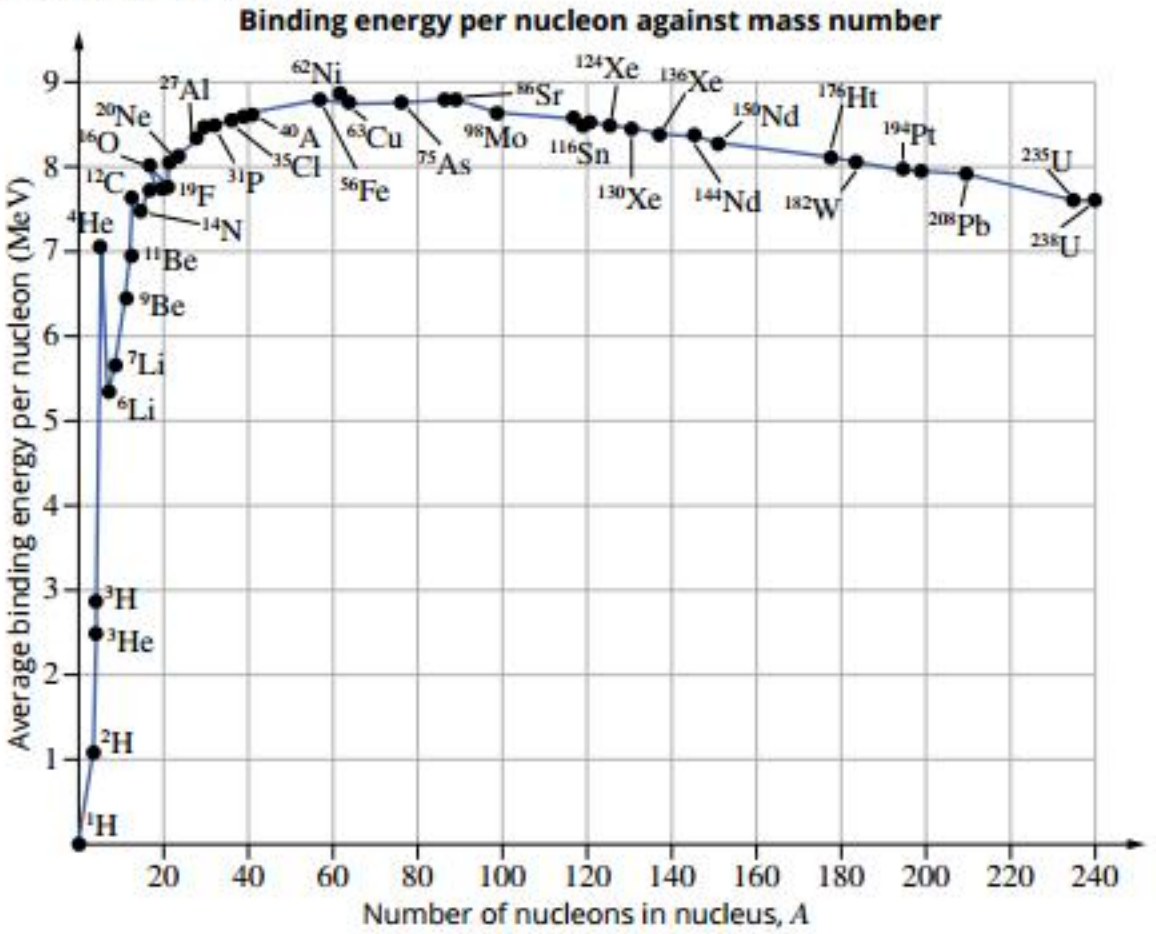


FIGURE 3.5.9 Graph of binding energy per nucleon for nuclei with mass numbers up to 240

A graph of the binding energy per nucleon against mass number has a rapid rise to a peak at nickel-62, then a gentler decline.

There are several important features to note:

- There is a peak in binding energy per nucleon at nickel-62 (atomic number 28).
- Nuclei with low mass numbers tend to have low binding energy per nucleon, although $^{4}_{2}$He (an alpha particle) does not follow this trend.
- There is a rapid rise in binding energy per nucleon from a mass number of 2 to nickel-62.
- There is a gentler decrease in binding energy per nucleon for nuclei with mass number greater than 62.

Nickel-62 has the highest binding energy per nucleon of all known isotopes. It is located very near to the isotopes iron-58 (atomic number 26) and iron-56, which are the second and third most tightly bound nuclei known. Isotopes heavier than nickel-62 are less stable because the diameter of their nuclei is too large for the attractive strong nuclear force to overcome the repulsive electrostatic force.

This curve will be used extensively in the final module of this chapter when you look at two specific types of nuclear reaction: fission and fusion.

Worked example 3.5.9

BINDING ENERGY PER NUCLEON CURVE

Use the graph in Figure 3.5.9 to compare the nuclear stability of oxygen-16 and beryllium-9.	
Thinking	**Working**
The approximate binding energy per nucleon for oxygen-16 and beryllium-9 can be read directly from the graph.	Binding energy per nucleon of oxygen-16 is approximately 8 MeV per nucleon. Binding energy per nucleon of beryllium-9 is approximately 6.5 MeV per nucleon.
The higher the binding energy per nucleon, the more tightly the nucleus is bound and the more stable it is.	8 MeV > 6.5 MeV So, the nucleus of oxygen-16 is held together more tightly than a nucleus of beryllium-9.

➤ Try yourself 3.5.9

BINDING ENERGY PER NUCLEON CURVE

Use the graph in Figure 3.5.9 to calculate the approximate binding energy of carbon-12.

3.5 Review

SUMMARY

- The electron volt (eV) is a unit of energy equal to 1.602×10^{-19} J. It is a non-SI unit but is preferred for use in nuclear physics as it is more convenient than joules.
- An isotope can be intentionally changed into another isotope by bombarding it with another particle in a process called artificial transmutation.
- Artificial transmutation is different from natural radioactive decay because decay is a naturally occurring process while artificial transmutation requires the input of energy, usually in a nuclear reactor or particle accelerator.
- The atomic mass unit (u) is a unit of mass used to measure the masses of nuclei and subatomic particles. It is equivalent to 1.66054×10^{-27} kg.
- In most nuclear reactions, the sum of the masses of the reactants will not equal the sum of the masses of the products. This difference is known as the mass defect, Δm.
- A nuclear reaction will not proceed naturally if the mass defect is a negative number because that reaction requires energy, rather than releases it.
- The energy required to break a nucleus completely into its constituent protons and neutrons is called the binding energy, ΔE.
- The binding energy can be calculated by using Einstein's famous mass–energy equivalence relationship:

$$\Delta E = \Delta m c^2$$

- One atomic mass unit (u) is equivalent to an energy of 931.6 MeV.
- The binding energy per nucleon is equal to the binding energy of a nucleus divided by the number of nucleons in that nucleus. It is a way of measuring the stability of a nucleus.
- A graph of binding energy per nucleon against mass number shows a curve with a peak at nickel-62. The higher a nuclei appears on the curve, the more stable it is.

KEY QUESTIONS

Describe

1 Convert 6.0×10^{-15} J to eV and MeV.

2 How many kilograms are there in one atomic mass unit?

3 Identify the isotope that has the highest binding energy per nucleon.

4 State how much energy is released when exactly 1 u of mass is converted into energy.

Apply

5 Describe how artificial transmutation is different from radioactive decay.

6 Explain why a nuclear reaction will not proceed naturally if the mass defect is negative.

7 Using the mass–energy equivalence relationship, calculate how much energy is released if 1.00 kg of matter is converted into energy.

8 Identify the particle X in each of the following reactions.

a ${}^{9}_{4}\text{Be} + {}^{4}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C} + \text{X}$

b ${}^{14}_{7}\text{N} + \text{X} \rightarrow {}^{14}_{6}\text{C} + {}^{1}_{1}\text{H}$

9 The artificial transmutation of cobalt-59 takes place in the core of a nuclear reactor. To create the new radioisotope cobalt-60, what must the parent nucleus be bombarded with?

3.5 Review *continued*

Analyse

10 Consider the following nuclear reaction:

$$^{23}_{11}\text{Na} \rightarrow {}^{19}_{9}\text{F} + {}^{4}_{2}\text{He}$$

The following data could be useful:

Mass of sodium-23 = 22.9897 u

Mass of fluorine-19 = 18.9984 u

Mass of helium-4 = 4.002 604 u

- **a** Determine the mass defect for the reaction.
- **b** Deduce whether this reaction will proceed naturally.

11 Show that the energy equivalent of a single electron is 0.511 MeV.

12 The power output of the Sun is 3.83×10^{26} W ($J s^{-1}$). Determine how much matter is converted into energy each second to account for this amount of power.

13 Beryllium-8 (mass = 8.005 305 10 u) is radioactive and undergoes alpha decay.

- **a** Write the full nuclear equation for this decay.
- **b** Determine how much energy is released by this decay in keV.

14 Phosphorus-32 (mass = 31.973 907 27 u) is a radioactive isotope and undergoes beta negative decay to give the daughter isotope sulfur-32 (mass = 31.972 071 00 u).

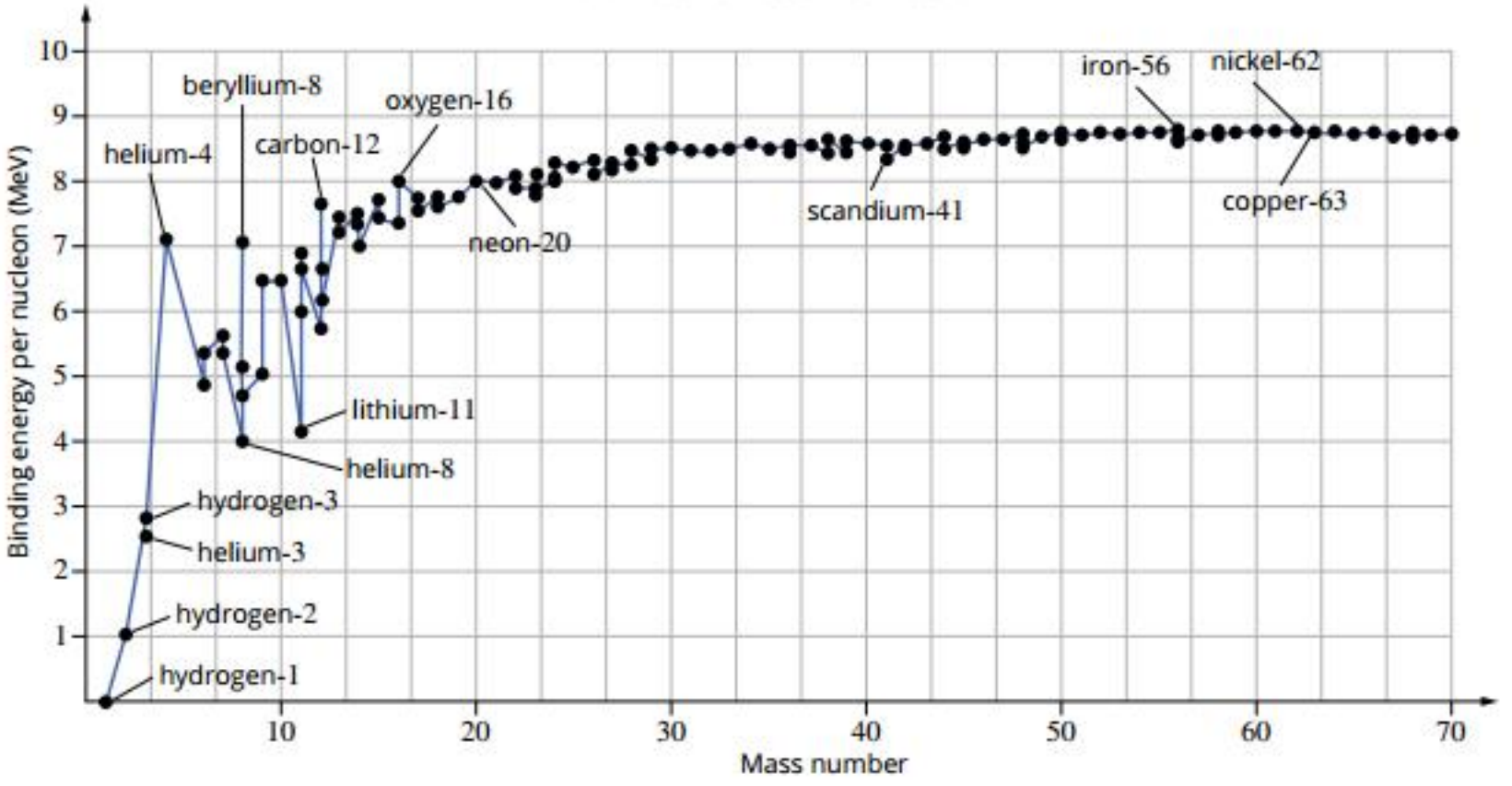
- **a** Write the full nuclear equation for this decay.
- **b** Determine how much energy is released by this decay in MeV.

15 A lithium-7 nucleus is bombarded with an alpha particle in an artificial transmutation experiment to create an isotope of another element. Write the full nuclear equation for this reaction if a neutron is also created in the experiment.

16 The graph below shows the binding energy for selected isotopes.

- **a** Identify the isotope that is the most stable: oxygen-16, helium-8 or iron-56.
- **b** Determine the binding energy of a nucleus of scandium-41.
- **c** Use the binding energy per nucleon of carbon-12 to approximately determine its nuclear mass and isotope mass.

Binding energy per nucleon for selected isotopes with mass numbers from 1 to 70



3.6 Fission and fusion

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that nuclear fission occurs when a nucleus is made to split and release a number of neutrons along with a large amount of energy
- recall that nuclear fission can be induced by bombarding a fissile nucleus with a neutron
- understand that a fissile nucleus is one that can absorb a neutron and undergo nuclear fission
- understand that at least one neutron per fission reaction is produced and that a chain reaction occurs when the free neutrons collide with further fissile nuclei, resulting in an exponential increase in the number of fission reactions and energy released
- understand that when a large nucleus such as uranium splits into two fragments, the binding energy per nucleus increases; this is the energy released during fission
- understand that nuclear fusion is the combining of light nuclei to form heavier nuclei. Extremely high temperatures and pressures are needed for fusion to occur
- explain that the amount of energy released per nucleon is greater for fusion than for fission reactions
- recall that as nucleons fuse together, the binding energy per nucleon increases; this is the energy released during fusion.

Einstein's mass–energy equivalence equation, $\Delta E = \Delta mc^2$, can be used to find the amount of energy produced in nuclear decay, and binding and bombardment reactions. This equation calculates the amount of energy released when a unit mass is completely converted into energy. There are two more classes of nuclear reactions that also release large amounts of energy. One of these, nuclear fission, is a source of power for many countries around the world, and the other, nuclear fusion, is the most common reaction of any sort in the universe.

NUCLEAR FISSION

Just before World War II broke out, four German physicists, Otto Hahn, Lise Meitner, Fritz Strassmann and Otto Robert Frisch, discovered **nuclear fission** of a uranium isotope. Nuclear fission is a process in which a heavy and unstable nucleus is forced to split into lighter nuclei. Specifically, a single, slow-moving neutron can be absorbed by the heavy nucleus, which causes the nucleus to become very unstable and split into fragments. As the nucleus splits, it releases a large amount of energy and smaller particles, as shown in Figure 3.6.1.

Most daughter nuclei of fission reactions are radioactive themselves, and will decay, but usually at a slower rate. Fission is primarily used in the production of electricity in a nuclear reactor, and in nuclear weapons. Note that nuclear fission is not the same as natural radioactive decay.

The most common example of a radioisotope that can undergo fission is uranium-235. This fission reaction starts with the bombardment of the uranium-235 nucleus with a single, relatively slow-moving neutron to produce uranium-236. The extra neutron is absorbed into the uranium-235 nucleus.

Nuclear fission is the process in which a large nucleus is forced to split into at least two approximately equal-sized fragments with the release of neutrons and energy.

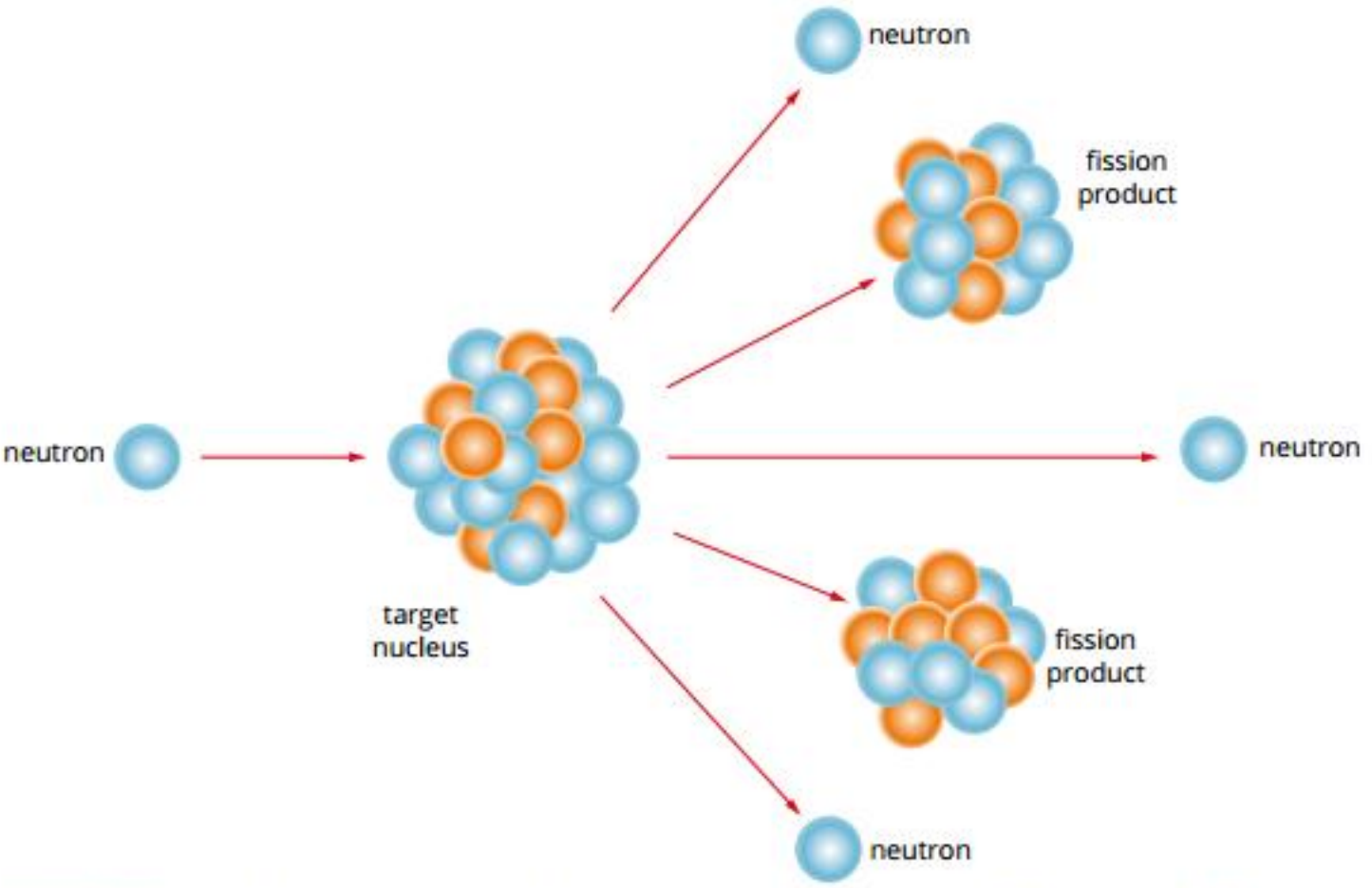


FIGURE 3.6.1 The nuclear fission reaction in which a target is bombarded with a smaller particle (usually a neutron) that causes the target to split into two approximately equal-sized pieces with more neutrons produced

The strong nuclear force cannot overcome the electrostatic forces within this nucleus, so the uranium-236 nucleus breaks apart into at least two similar-sized nuclei along with a few neutrons and a large amount of energy.

These nuclear fission reactions are summarised below:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{236}_{92}\mathrm{U}$$

$$^{236}_{92}\mathrm{U} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$$

Note that the uranium-236 is not decaying into barium-141 and krypton-92 but creating **fission fragments** of these daughter isotopes. The fission fragments are usually very radioactive and therefore dangerous to living tissue.

The above reaction is just one combination of the ways in which uranium-236 can be fragmented. Other examples include:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{236}_{92}\mathrm{U} \rightarrow ^{143}_{55}\mathrm{Cs} + ^{90}_{37}\mathrm{Rb} + 3^{1}_{0}\mathrm{n}$$

or

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{236}_{92}\mathrm{U} \rightarrow ^{90}_{38}\mathrm{Sr} + ^{143}_{54}\mathrm{Xe} + 3^{1}_{0}\mathrm{n}$$

As long as the atomic numbers and mass numbers are conserved, there are many other fragment pairs that can result from this fission reaction. The fragments usually range from germanium (Z = 32) to samarium (Z = 62). The general fission of uranium-235 is shown in Figure 3.6.2.

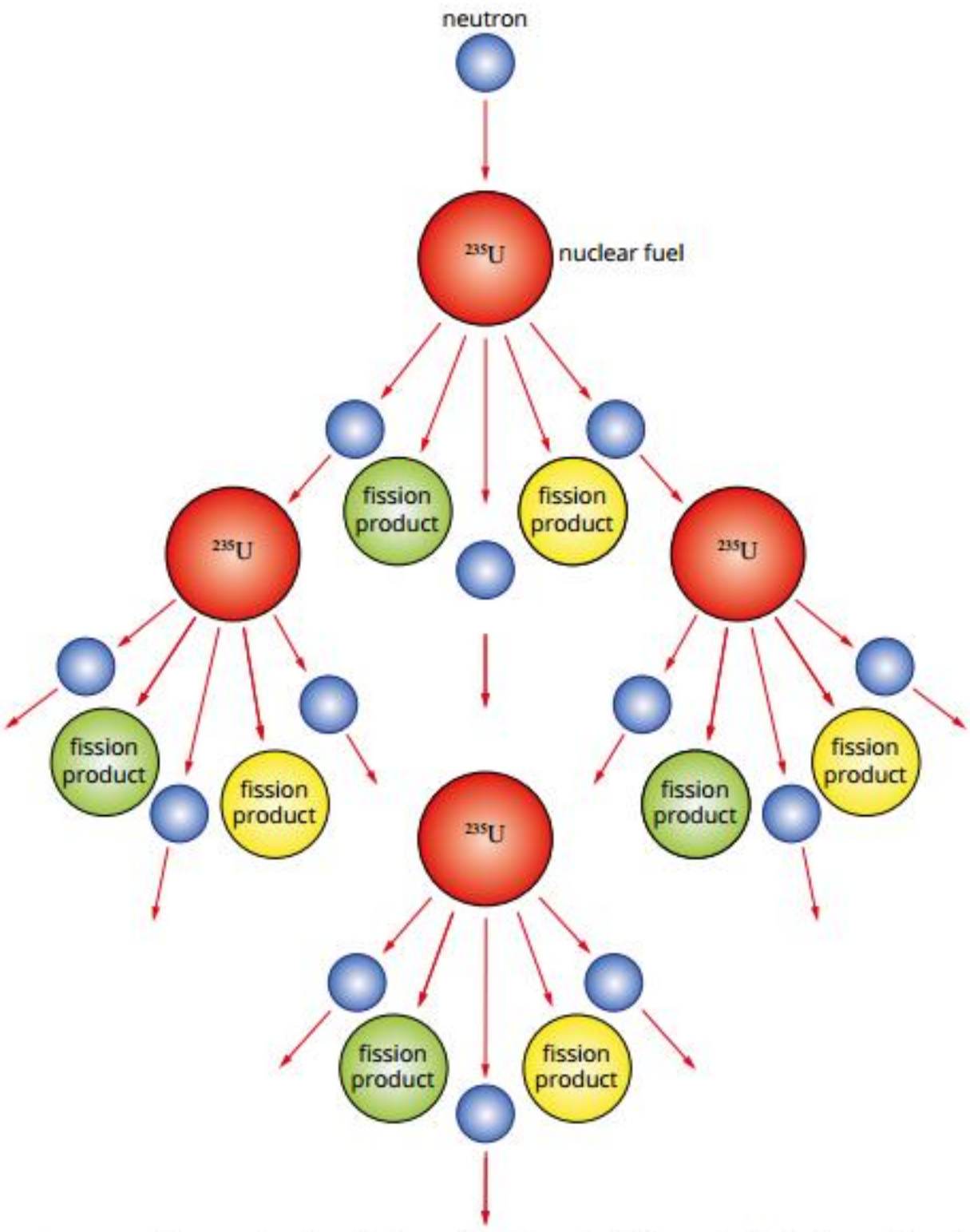


FIGURE 3.6.2 The general nuclear fission reaction of uranium-235 creates fission fragments and three neutrons.

Typically, the percentage of mass of the original heavy isotope that is converted into energy is around 0.1%, and the amount of energy created in a nuclear fission reaction is often more than 100 times that produced in natural radioactive decay. To calculate the amount of energy released in a single nuclear fission reaction, you apply the same reasoning as to calculating the mass difference in alpha decay.

$$\text{Mass difference} = \text{mass of reactants} - \text{mass of products}$$

$$\text{Energy} = \text{mass difference} \times 931.6\,\text{MeV per u}$$

The energy released by nuclear fission is calculated in the same way as decay reactions, in which the mass defect is multiplied by 931.6 MeV.

Worked example 3.6.1

ENERGY FROM NUCLEAR FISSION

When a uranium-235 nucleus is bombarded with a single neutron, it fragments into three neutrons, caesium-137 and rubidium-96.

a Write the equation for this nuclear fission reaction and calculate the energy released.

Thinking	Working
This is a nuclear fission reaction so there are two reactants: uranium-235 and a neutron. There are five products: caesium-137; rubidium-96 and three neutrons. The number of electrons is conserved in fission reactions, so the masses of the isotopes can be used instead of the nuclear masses.	${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{137}_{55}\text{Cs} + {}^{96}_{37}\text{Rb} + 3{}^{1}_{0}\text{n}$

b Determine the percentage of the original mass of the uranium-235 that was converted into energy.

The required masses are:
neutron = 1.008 665 u
uranium-235 = 235.043 929 9 u
caesium-137 = 136.907 089 5 u
rubidium-96 = 95.934 27 u

Thinking	Working
Find the difference between the masses of the reactants and the products. mass difference = mass of reactants – mass of products	mass of reactants = 235.043 929 9 + 1.008 665 = 236.052 594 9 u mass of products = 136.907 089 5 + 95.934 27 + 3 × 1.008 665 = 235.867 354 5 u mass difference = 236.052 594 9 – 235.867 354 5 = 0.185 240 4 u Note that the mass difference is a positive value, so the nuclear fission reaction will proceed, but it would not proceed if the neutron had not bombarded the uranium-235 nucleus initially.
Find the amount of energy equivalent to the mass difference by multiplying the mass difference by 931.6 MeV per u.	energy released = 0.185 240 4 × 931.6 = 172.6 MeV
The percentage of mass lost from uranium-235 is found by dividing the mass difference by the mass of the uranium-235 and multiplying by 100.	$\text{percentage of mass lost} = \frac{0.1852404}{235.0439299} \times 100$ = 0.079%

➤ Try yourself 3.6.1

ENERGY FROM NUCLEAR FISSION

A plutonium-239 nucleus is bombarded with a single neutron and fragments into xenon-134 and zirconium-103, with the release of three neutrons.

a Write the nuclear fission reaction for this process.

b Calculate the percentage of the original mass of the plutonium-239 that is converted into energy.

The required masses are:
Mass of neutron = 1.008665 u
Mass of plutonium-239 = 239.0521634 u
Mass of xenon-134 = 133.9053945 u
Mass of zirconium-103 = 102.92660 u

An important feature of nuclear fission is the production of extra neutrons, which can go on to react with other **fissile** nuclei to trigger more fission reactions. If three neutrons are released in a single fission reaction, then those neutrons can trigger three more fission reactions by bombarding more fissile material. Each of those fission reactions then produces three more neutrons, releasing 9, then 27, then 81 neutrons, and so on. This exponential cascade of more neutrons initiating more fission reactions is called a **chain reaction**, as shown in Figure 3.6.3.

A chain reaction occurs when a single nuclear reaction causes a dramatic increase in the number of successive nuclear reactions.

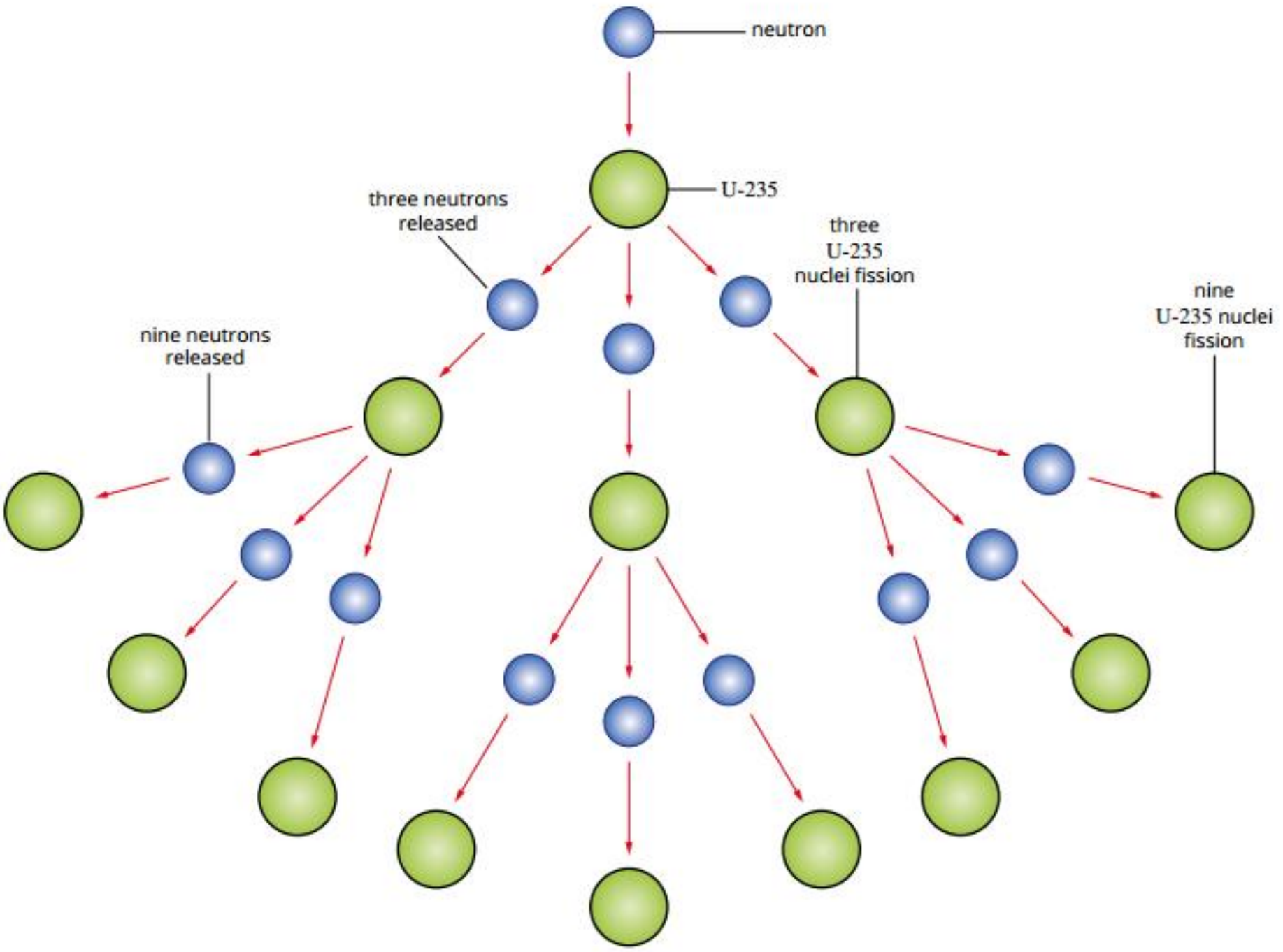


FIGURE 3.6.3 The start of a chain reaction involving uranium-235. Each fission reaction produces three neutrons, which then go on to react with three other uranium-235 nuclei to create nine new neutrons, and so on, in a runaway series of reactions producing very large amounts of energy.

After only 13 series of reactions there will be over one million neutrons available to trigger that many fission reactions. The number of fission reactions occurring at one given time during a chain reaction is increasing, so the amount of energy produced also increases.

Chain reactions continue for as long as there is enough material available. The amount of material needed to sustain a chain reaction is known as the **critical mass**. Inside nuclear reactors the amount of fissile material is controlled. The number of neutrons available for reactions can be kept reasonably constant, rather than increasing exponentially, using control rods made of a material that absorbs neutrons, such as graphite. This allows a controlled chain reaction. However, in a nuclear weapon there is enough material to sustain an uncontrolled chain reaction and Figure 3.6.4 is the result.

FIGURE 3.6.4 The unmistakable mushroom cloud formed by an unregulated chain reaction of uranium-235 or plutonium-239 in a nuclear bomb. This photograph was taken in 1971 by the French army when they conducted nuclear weapons testing at Moruroa Atoll in the Pacific Ocean.

NUCLEAR FUSION

Nuclear fission is the result of a heavy nucleus splitting into two or more smaller nuclei with the release of energy and particles. The opposite type of reaction in which two smaller nuclei combine to produce a heavier nucleus and energy is known as **nuclear fusion**. Fusion occurs when two light nuclei (usually isotopes of hydrogen or helium) join together to make a heavier and more stable nucleus. The mass of the new nucleus is lighter than the sum of the nuclei that fused to form it, so energy will be released in this process.

Nuclear fusion is the process whereby two smaller nuclei join, or fuse, together to create a larger nucleus with the release of energy.

Fusion reactions, specifically the reaction of two protons joining to make helium, are, by far, the most common type of nuclear or chemical reaction in the universe. They produce the second highest amount of energy per kilogram of matter, only behind matter–antimatter annihilation reactions.

In order for fusion to occur, two conditions must be met.

1 The smaller nuclei must be travelling very fast. To achieve this the particles must have a very high temperature of about 10 million kelvin.
2 There need to be enough nuclei available to sustain a fusion reaction. This occurs under high pressure.

Both conditions of high speed and high pressure are easily met in the cores of stars, and a long time ago at the Big Bang. Currently, no nuclear fusion reactor on Earth can sustain a fusion reaction with a net output of energy, but research continues in the USA, Asia and Europe (Figure 3.6.5).

FIGURE 3.6.5 The inside of a nuclear fusion reactor design called a tokamak at the Joint European Torus in England

A very common nuclear fusion reaction that occurs inside the cores of stars the size of the Sun is the fusion of ${}^{2}_{1}\mathrm{H}$ (the nucleus of deuterium, or hydrogen-2) with a proton, ${}^{1}_{1}\mathrm{H}$. This reaction produces ${}^{3}_{2}\mathrm{He}$ and energy in the form of a gamma ray. The reaction is written as:

$$ {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{0}\gamma $$

Note that even though this reaction produces a gamma ray, it is not the same as gamma decay.

As in nuclear fission, some of the products of a fusion reaction are smaller particles. An example of a fusion reaction that occurred about one minute after the Big Bang is the reaction of the nucleus of deuterium with the nucleus of tritium (Figure 3.6.6).

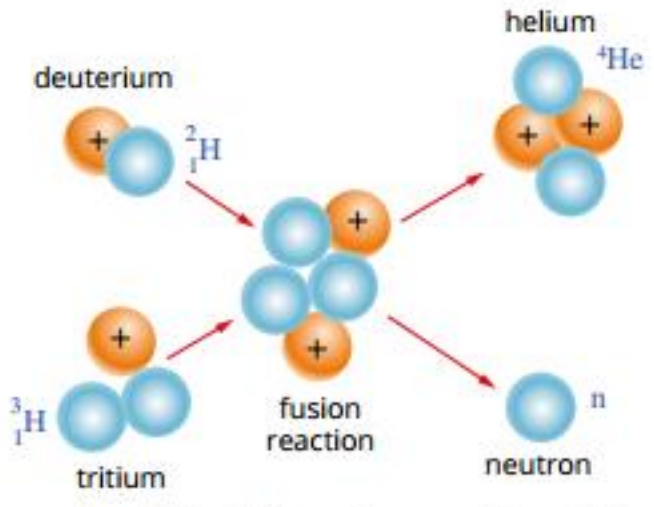


FIGURE 3.6.6 The fusion reaction of ${}^{2}_{1}\mathrm{H}$ with ${}^{3}_{1}\mathrm{H}$ produces an alpha particle, a neutron and energy.

This produces an alpha particle, a free neutron and energy:

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} $$

Inside the cores of the largest stars, fusion reactions of an alpha particle with heavier nuclides can take place that produce nuclides up to ${}^{56}_{28}\mathrm{Ni}$. The heaviest nuclide that can fuse with an alpha particle is, therefore, ${}^{52}_{26}\mathrm{Fe}$ because it produces ${}^{56}_{28}\mathrm{Ni}$ in the following reaction:

$$ {}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{56}_{28}\mathrm{Ni} $$

Fusion of nuclides heavier than ${}^{56}_{28}\mathrm{Ni}$ actually *require* energy rather than *produce* energy and so will not proceed.

> **i** The energy released by nuclear fusion reactions is calculated in the same way as for decay reactions, in which the mass defect is multiplied by 931.6 MeV.

The amount of energy created in a nuclear fusion reaction is usually lower than that produced in a nuclear fission reaction, but the energy per mass of reactants is much higher, around 0.5% of the fusing particles. Again, to calculate the amount of energy released in a nuclear fusion reaction, you apply the same reasoning used in nuclear fission reactions:

$$\text{mass difference} = \text{mass of reactants} - \text{mass of products}$$
$$\text{energy} = \text{mass difference} \times 931.6\,\text{MeV per u}$$

Worked example 3.6.2

ENERGY FROM NUCLEAR FUSION

A deuterium (hydrogen-2) nucleus fuses with a tritium (hydrogen-3) nucleus to produce an alpha particle and a neutron.

a Write the equation for this nuclear fusion reaction.

Thinking	Working
There are two reactants: a deuterium nucleus and a tritium nucleus. There are two products: an alpha particle and a neutron.	${}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$

b Calculate the energy released by the process and, hence, the percentage of the mass of the reactants that has been converted into energy.

The required masses are:
neutron = 1.008 665 u
deuterium atom = 2.014 101 78 u
tritium atom = 3.016 049 2 u
alpha particle = 4.001 506 u
electron = 0.000 548 6 u

Thinking	Working
Calculate the difference between the mass of the reactants and the products. Note that because the masses of the deuterium and tritium isotopes, and the mass of the alpha particle (without any electrons) are given, the masses of two electrons will need to be subtracted from the reactants to keep everything in terms of nuclear masses.	mass of deuterium nucleus = mass of deuterium isotope – mass of electron = 2.014 101 78 – 0.000 548 6 = 2.013 553 18 u mass of tritium nucleus = mass of tritium isotope – mass of electron = 3.016 049 2 – 0.000 548 6 = 3.015 500 6 u mass of reactants = 2.013 553 18 + 3.015 500 6 = 5.029 053 78 u mass of products = 4.001 506 + 1.008 665 = 5.010 171 u mass difference = 5.029 053 78 – 5.010 171 = 0.018 882 78 u Note that the nuclear fusion reaction will proceed because the mass difference is a positive value.
Find the amount of energy this is equivalent to by using 931.6 MeV per u.	energy released = 0.018 882 78 × 931.6 = 17.59 MeV
The percentage of the masses of the reactants that has been converted into energy is found by dividing the mass difference by the sum of the masses of the reactants and then multiplying by 100.	$\text{percentage of reactants mass lost as energy} = \frac{0.018\,882\,78}{5.029\,053\,789} \times 100$ = 0.38%

➤ Try yourself 3.6.2

ENERGY FROM NUCLEAR FUSION

An important nuclear fusion reaction that occurs inside stars heavier than the Sun is the combining of a carbon-12 nucleus with an alpha particle to create a heavier nucleus and energy in the form of a gamma ray.

The required masses are:

carbon-12 atom = 12.0000000 u

daughter isotope = 15.994 914 619 56 u

alpha particle (nucleus only) = 4.001 506 u

electron = 0.000 548 6 u

a Write the nuclear fusion reaction for this process.

b Determine the nuclide created in this reaction.

c Calculate the energy released from this reaction.

d Calculate the percentage of the mass of reactants that has been converted into energy.

FISSION, FUSION AND THE BINDING ENERGY PER NUCLEON CURVE

Nuclear fission reactions produce energy when heavy nuclei split into two or more lighter nuclei. Nuclear fusion reactions produce energy when two lighter nuclei combine to produce a heavier nucleus.

Fusion reactions produce energy up to the creation of mass number 62, which is nickel-62. Fission reactions produce energy for products down to nickel-62. This is seen more clearly in the binding energy per nucleon graph in Figure 3.6.7.

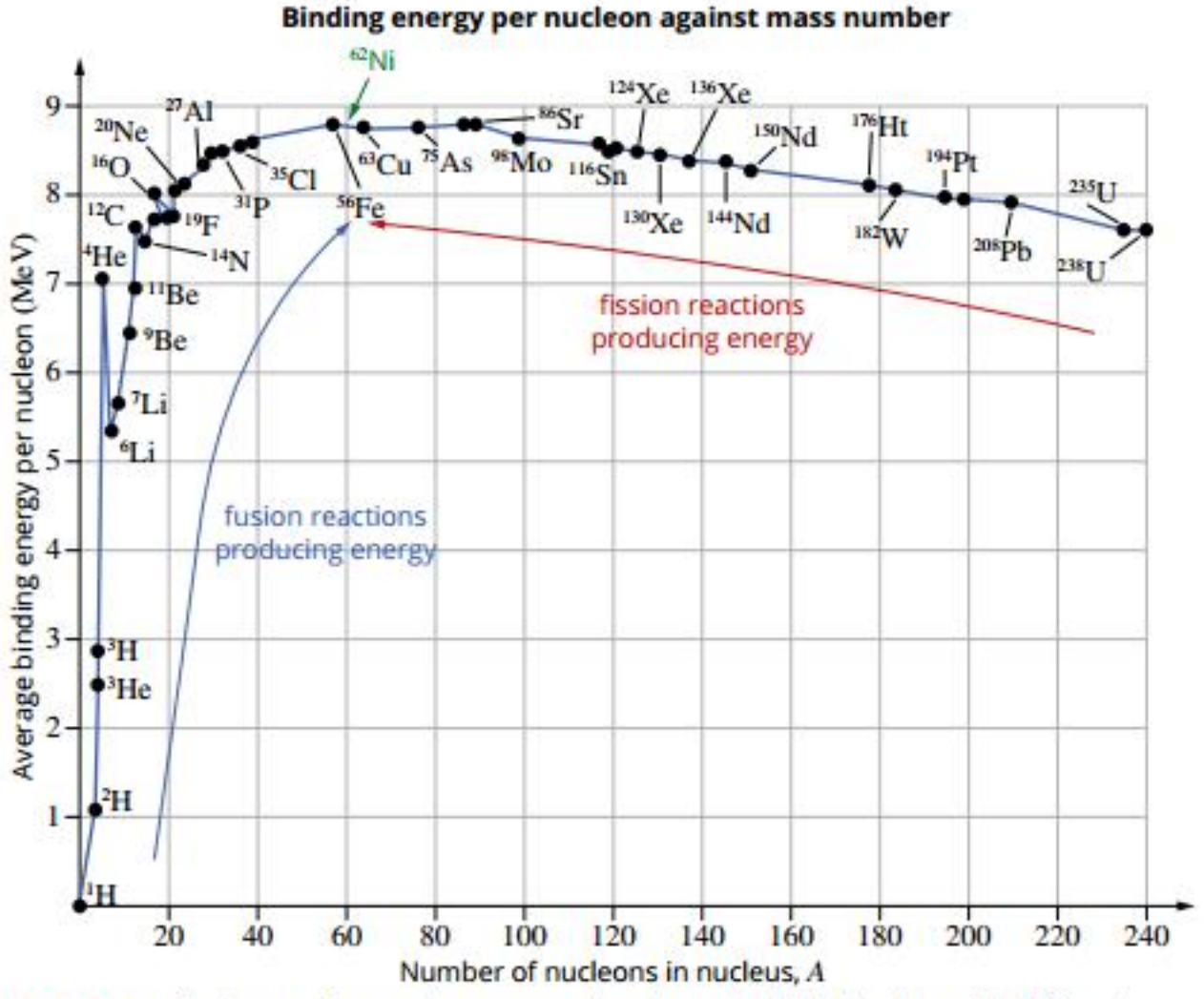


FIGURE 3.6.7 Fusion reactions produce energy when the product is lighter than nickel-62, and fission reactions produce energy when the product is heavier than nickel-62.

There are other important features of this graph:

- Fusion reactions produce energy when their products are higher on the graph (they have a greater binding energy per nucleon) than their reactants. This is especially important when fusion of nuclides such as helium-4 is occurring because of the local peak in the graph at this nuclide.
- Similarly, fission reactions will produce energy when their products are higher on the graph than their reactants.
- Fusion reactions do not occur if their products are heavier than nickel-62, because those reactions require energy to proceed.
- Fission reactions do not occur if their products are lighter than nickel-62, because those reactions also require energy to proceed.
- The fusion part of the graph is steeper. This means that a small change in mass number for low-mass nuclei produces more energy than a similar change in mass number for high-mass nuclei. Another way to say this is that a higher percentage of mass is being converted into energy in fusion than occurs in fission, or that there is more energy released per nucleon in fusion than in fission.

Nuclear *fission* reactions produce energy if the products are heavier than nickel-62 (have a mass number larger than 62).

Most nuclear *fusion* reactions produce energy if the products are lighter than nickel-62 (have a mass number smaller than 62).

3.6 Review

SUMMARY

- Nuclear fission occurs when a nucleus is made to split and release a number of neutrons along with a large amount of energy.
- Nuclear fission can be induced by bombarding a fissile nucleus with a neutron.
- A fissile nucleus is one that can absorb a neutron and undergo nuclear fission.
- If a large nucleus such as uranium splits into two fragments, the binding energy per nucleon also increases. This is the energy released during fission.
- When fission occurs, the mass of the fission fragments is always less than the mass of the original particles. This decrease in mass is proportional to energy, as given by $\Delta E = \Delta mc^2$.
- In a fission reaction, at least one neutron per fission is produced. A chain reaction occurs when the free neutrons collide with further fissile nuclei, resulting in an exponential increase in the number of fission reactions and energy released.
- Nuclear fusion is the combining of light nuclei to form heavier nuclei. Extremely high temperatures and pressures are needed for fusion to occur.
- A small amount of mass is lost during a fusion reaction. This mass is related to the energy produced according to $\Delta E = \Delta mc^2$.
- Nuclei are positively charged and so repel each other due to electrostatic forces. Approaching nuclei must have enough speed and pressure to overcome the electrostatic forces and get close enough for the strong nuclear force to take effect.
- The amount of energy released per nucleon is greater for fusion than for fission reactions.
- As nucleons fuse together, the binding energy per nucleon increases. This is the energy released during fusion.

KEY QUESTIONS

Describe

1 Describe the terms 'fissile' and 'chain reaction'.

2 List three similarities between nuclear fission and nuclear fusion.

3 Describe the concept of 'binding energy per nucleon'.

Apply

4 Describe how nuclear fission differs from radioactive decay.

5 Explain why nuclear fission is generally considered to be a non-natural process.

6 Explain why slow-moving neutrons are needed for fission to occur, but very fast-moving particles are needed for fusion to occur.

7 On the binding energy per nucleon graph shown in Figure 3.6.7 on page 109, identify which isotope has the highest binding energy per nucleon.

8 Explain why fusion requires enormous temperatures and pressures.

Analyse

9 Explain why nuclear fusion reactions produce so much more energy per kg than nuclear fission reactions.

10 Plutonium-239 is a fissile material. When a plutonium-239 nucleus is struck by, and absorbs, a neutron, it can fragment in many ways. Consider the example of a nucleus of plutonium-239 that splits into barium-145 and strontium-93 and releases some neutrons.

a Determine the number of neutrons.

b Write the full fission reaction for this process.

c Calculate how much energy is released in this reaction by determining the mass difference for the following masses of isotopes:

Plutonium-239 mass = 239.052 163 4 u
Neutron mass = 1.008 665 u
Barium-145 mass = 144.927 63 u
Strontium-93 mass = 92.914 026 u

d Determine the percentage of the original plutonium-239 isotope that was converted into energy.

11 The following fusion reaction is taking place inside the core of the Sun:

$$^{3}_{2}\text{He} + \text{X} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{1}\text{H} + {}^{1}_{1}\text{H}$$

During each reaction, 23.0 MeV of energy is released.

a Determine the atomic and mass numbers and symbol of particle X.

b Calculate how much energy is released per reaction in joules.

c Determine the mass defect for this fusion reaction.

Chapter review

03

KEY TERMS

alpha particle
alpha radiation
antineutrino
artificial transmutation
atomic number
beta negative radiation
beta particle
beta positive radiation
binding energy
binding energy per nucleon
chain reaction
coulomb
coulomb force
critical mass
daughter nucleus
decay
decay series
electromagnetic wave
electron
electron volt
electrostatic force
fissile
fission fragments
gamma radiation
gamma ray
half-life
ionisation
ionising radiation
isotope
mass defect
mass number
neutral
neutrino
neutron number
nuclear fission
nuclear fusion
nuclear reaction
nuclear reactor
nuclear transmutation
nucleon
nuclide
parent nucleus
particle accelerator
penetrating ability
positron
proton
radiation
radioactive
radioactivity
radioisotope
radionuclide
Segre plot
strong nuclear force
subatomic
transmutation
unified atomic mass unit

KEY QUESTIONS

Describe

1 Which of the following have seven neutrons in their nucleus? (More than one answer may be correct.)
- **A** carbon-12
- **B** carbon-13
- **C** carbon-14
- **D** nitrogen-14

2 How many protons and neutrons are there in the $^{45}_{20}Ca$ nuclide?

3 Use the periodic table (Figure 3.2.2) to determine the number of protons, neutrons and nucleons in cobalt-60.

4 Determine the nature of the unknown, X, for the following transmutation:

$$^{60m}_{27}Co \rightarrow {}^{60}_{27}Co + X$$

(60m means the nuclide is metastable and has a higher level of stability than very short-lived isotopes. The mass number is still 60.)

5 Identify each of these particles or radiation types:
- **a** $^{0}_{-1}A$
- **b** $^{1}_{1}B$
- **c** $^{4}_{2}C$
- **d** $^{1}_{0}D$
- **e** $^{0}_{0}E$
- **f** $^{0}_{1}F$

6 Describe the type of nucleus that generally produces an alpha particle.

7 Identify an example of a stable isotope that has more protons than neutrons.

Apply

8 Explain why a hypothetical nuclide that contains 10 protons and 6 neutrons will be unstable.

*Questions **9–11** refer to equations I–IV below:*

I $^{64}_{29}Cu \rightarrow {}^{64}_{28}Ni + {}^{0}_{1}\beta + {}^{0}_{0}\nu$

II $^{20}_{10}Ne + {}^{4}_{2}He \rightarrow {}^{24}_{12}Mg + {}^{0}_{0}\gamma$

III $^{256}_{102}No \rightarrow {}^{252}_{100}Fm + {}^{4}_{2}He$

IV $^{64}_{29}Cu \rightarrow {}^{64}_{30}Zn + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$

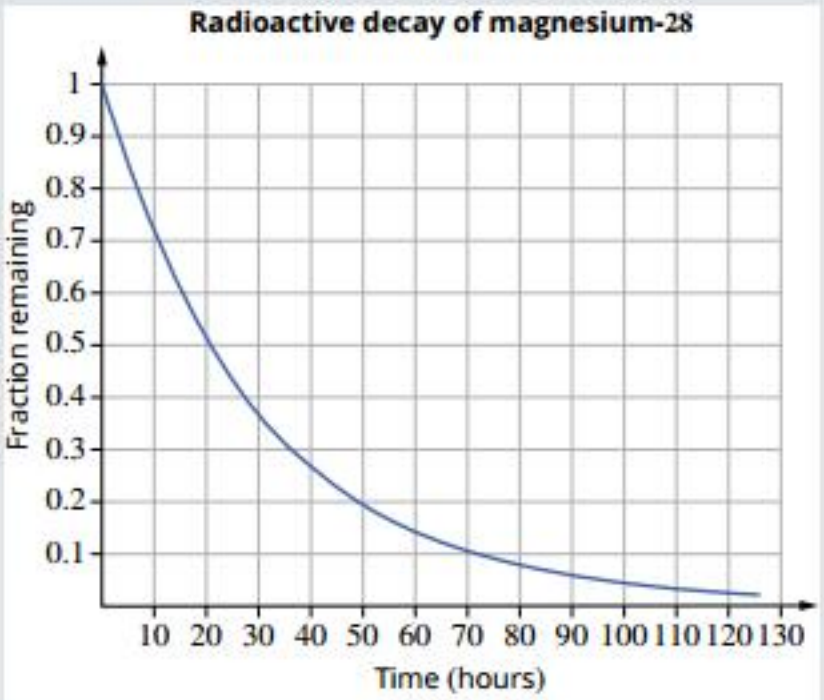
9 Which equation or equations show an example of a reaction that releases energy?
- **A** I, III and IV
- **B** III only
- **C** I and IV
- **D** I, II, III and IV

10 Which equation or equations show an example of a type of beta decay?
- **A** I, III and IV
- **B** III only
- **C** I and IV
- **D** I, II, III and IV

11 Which equation or equations show an example of alpha decay?

A I, III and IV
B III only
C I and IV
D I, II, III and IV

12 What information can be obtained about magnesium-28 from the following graph?



A decay mode
B activity after a given time
C number of nuclei remaining after a given time
D half-life

13 State, and explain, the type of decay that the following hypothetical nuclides will undergo:

a $^{100}_{5}B$
b $^{31}_{30}Zn$
c $^{156m}_{72}Hf$

14 Molybdenum-99 is a beta emitter with a half-life of 67 hours. It decays to form metastable technetium-99m, which has a half-life of 6 hours. This, in turn, decays to form technetium-99, which has a half-life of about 250 000 years.

a Identify the most stable of the three isotopes. Explain your choice.
b Identify the least stable of the three isotopes. Explain your choice.

15 Explain why nuclear chain reactions can produce very large amounts of energy very quickly if they are not controlled.

16 Sequence the following particles from smallest to largest mass: alpha particle, proton, neutron, beta negative particle, antineutrino, hydrogen-2 nuclide.

17 Most of the helium gas found on Earth is formed by the alpha decay of isotopes heavier than uranium. Use your knowledge of the penetrating ability of an alpha particle to explain why.

Analyse

18 Determine the percentage of the original material of a substance that remains after 4 half-lives.

A 25%
B 12.5%
C 6.25%
D 0%

19 The binding energy of the $^{147}_{62}Sm$ nuclide is 1217 MeV. Determine the binding energy per nucleon of $^{147}_{62}Sm$.

A 1217 MeV per nucleon
B 8.28 MeV per nucleon
C 19.6 MeV per nucleon
D 14.3 MeV per nucleon

*Questions **20** and **21** refer to the following nuclear reaction:*

$$^{249}_{98}Cf + ^{48}_{20}Ca \rightarrow ^{294}_{118}Og + 3\,^{1}_{0}n$$

20 Which is the correct method of calculating mass defect?

A mass of Cf-249 + mass of Ca-48 − mass of Og-294 − 3 × mass of neutron
B mass of Og-294 + 3 × mass of neutron × mass of Cf-249 − mass of Ca-48
C binding energy of products − binding energy of reactants
D binding energy of reactants − binding energy of products

21 What type of reaction does this equation show?

A nuclear fusion
B beta negative decay
C alpha decay
D artificial transmutation

22 Iodine-131 has a half-life of 8 days. A sample of the radioisotope initially contains 2.4×10^{12} iodine-131 nuclei. Determine how many iodine-131 nuclei remain after 24 days.

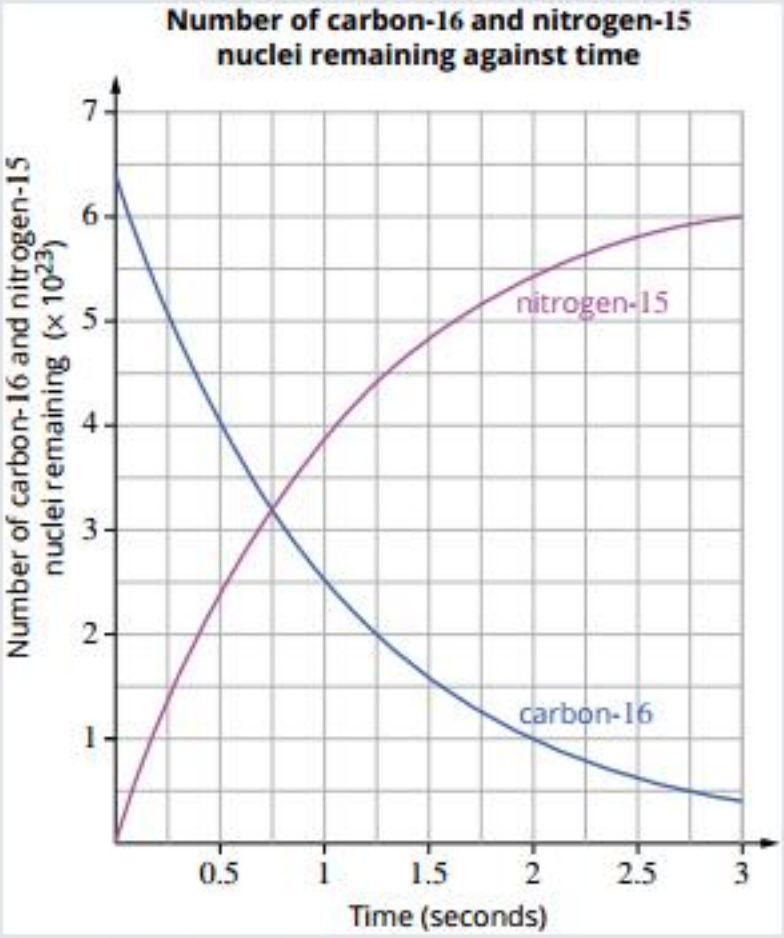
23 Calculate how much mass is converted to energy if 774 keV of energy is released during a particular decay reaction.

24 Calculate the binding energy and binding energy per nucleon for the following nuclides. The isotopic mass of each appears in brackets.

a $^{181}_{76}Os$ (180.95324 u)
b $^{40}_{19}K$ (39.96399848 u)

25 Calculate the percentage of the mass of the separate protons and neutrons that is converted into energy to form the $^{56}_{26}Fe$ nuclide. Iron-56 has a mass of 55.9349363 u.

Interpret



26 The graph shows the decay curve of the radioisotope carbon-16, which decays via beta negative radiation into the radioisotope nitrogen-16. It then emits a single neutron to become the stable isotope nitrogen-15. The graph shows the number of carbon-16 nuclei remaining in blue, and the number of nitrogen-15 nuclei created in purple.

- **a** Explain why the number of nitrogen-15 nuclei starts at zero.
- **b** Determine the half-life of carbon-16.
- **c** Explain why the curve of number of nitrogen-15 nuclei is increasing.
- **d** Discuss the meaning of the point of intersection of the number of carbon-16 and nitrogen-15 nuclei remaining.
- **e** Determine a conclusion that can be reached about the total of the number of carbon-16 plus nitrogen-15 nuclei remaining.
- **f** Argue, by presenting two different reasons, why you cannot determine the half-life of nitrogen-15 from this curve.

27 A free neutron (one that is not inside the nucleus of an atom) has a half-life of about 15 minutes.

- **a** What type of decay will it undergo?
- **b** Determine the full nuclear equation for this decay.
- **c** Determine how much energy is released when it decays.
- **d** Calculate the energy released (in J) in total if 500.0 g of plutonium-239 undergoes a typical nuclear fission reaction that produces 200.0 MeV. One atom of plutonium-239 has a mass of 239.0521634 u.

28 Uranium and lead are used to determine the ages of rocks in the Earth's crust. Specifically, the relative amounts of uranium-238 (half-life 4.48×10^8 years) and lead-206 (stable) tell us how long the uranium has had to decay into lead. If a rock containing 0.083 g of uranium-238 and 0.031 g of lead-206 is found, calculate the age of the rock.

29 Identify the mass numbers of the five stable nuclides of calcium (atomic number 20). Use the Segre plot on page 53 to answer this question.

Data analysis

DATA SET 1

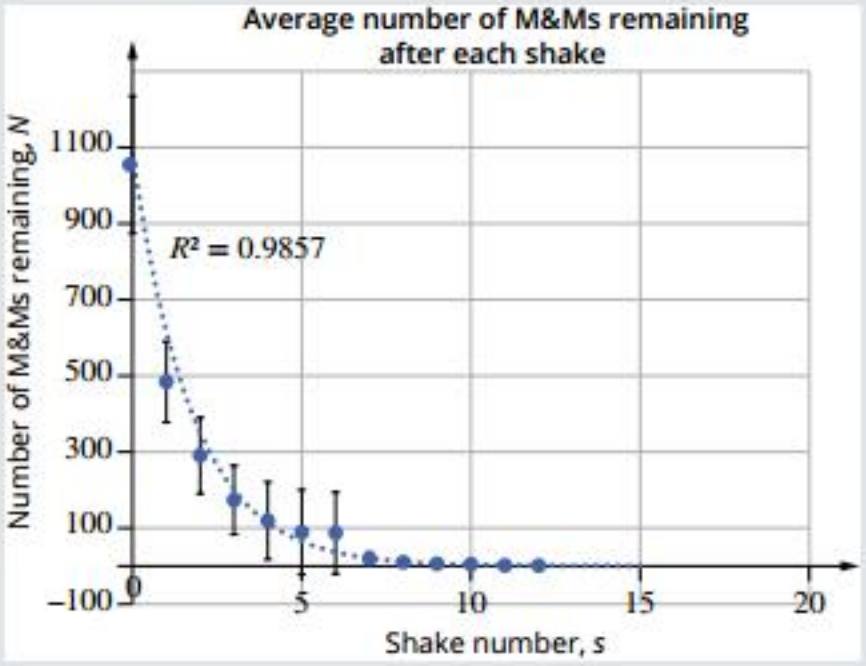
The information below applies to Questions 1–6.

Five physics students performed an experiment involving the 'decay' of a sample of M&M chocolate lollies. Initially, each student had approximately 1000 M&Ms.

Each student placed their M&Ms into a Tupperware container with the lid on and shook the container. The M&Ms were then emptied onto a piece of A3 paper and carefully separated so that all the individual M&Ms were visible.

Any M&Ms that had the 'm' symbol facing upwards were deemed to have 'decayed' and so were removed from the A3 paper. The remaining M&MS were counted, placed back into the Tupperware container, shaken and spread out onto the A3 paper again where the M&Ms with the 'm' symbol showing were, once more, removed.

This process continued until all the M&Ms had 'decayed', with the data shown below as a graph. The graph has an exponential trendline displayed as a dotted line:



The equation of the trendline is:

$$N = 1084.2 \times \left(\frac{1}{2}\right)^{0.8122s}$$

where N is the number of M&Ms remaining and s is the shake number.

Question 1 (1 mark)

Use the graph to determine the average number of M&Ms each student had at the start of the experiment.

Question 2 (1 mark)

Use the graph to determine how many shakes it took to reduce the number of surviving M&Ms to approximately 120.

Question 3 (2 marks)

Determine the 'half-life' of the M&Ms in this experiment to the nearest whole number of shakes. Use the graph to support your answer.

Question 4 (3 marks)

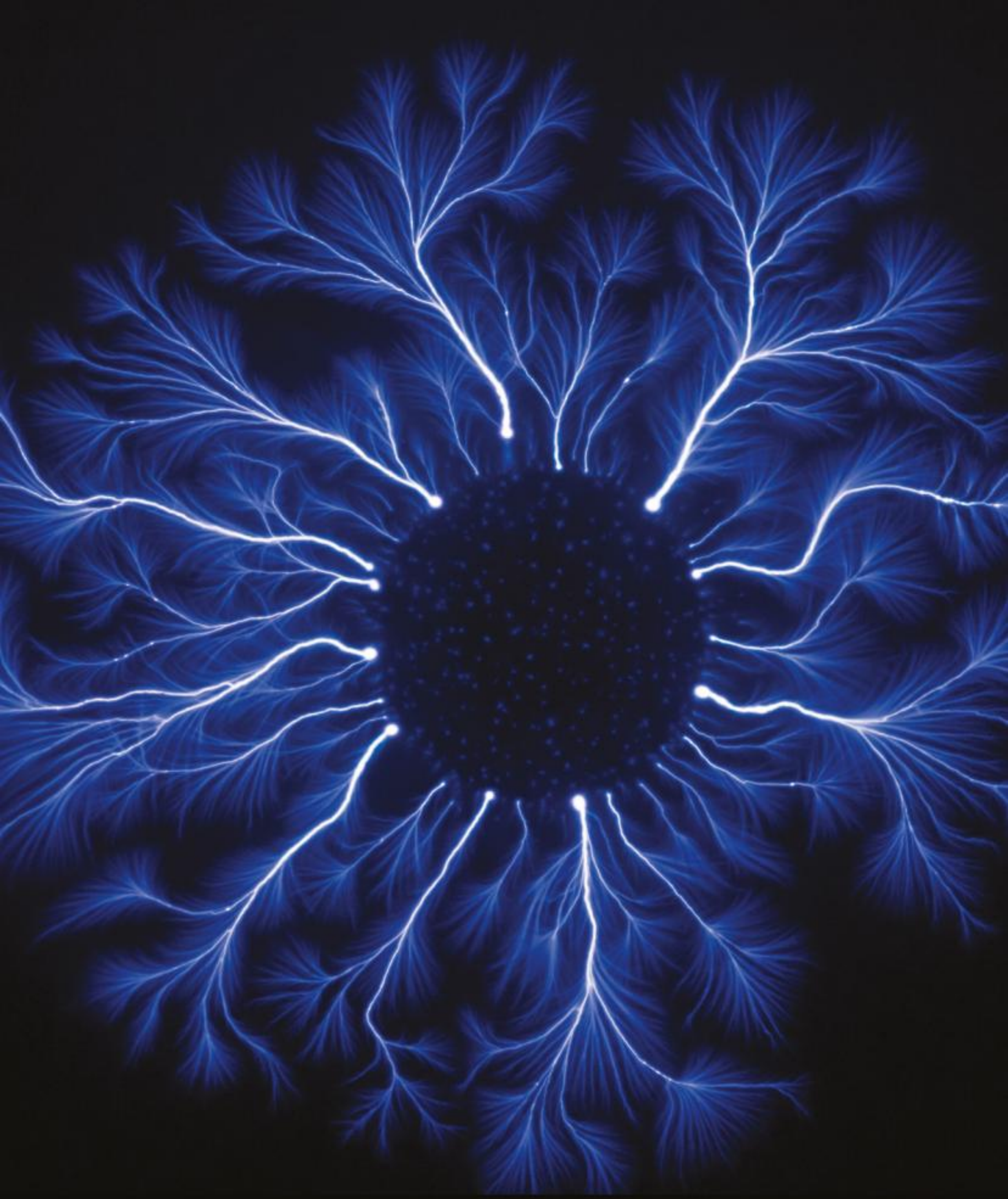
Use the equation of the trendline to determine an experimental value of the 'half-life' of the M&Ms in this experiment.

Question 5 (1 mark)

Calculate the percentage error between your experimental value and the theoretical value (1) of the 'half-life' of an M&M.

Question 6 (4 marks)

Draw a conclusion around the precision and validity of the experiment.



CHAPTER

04 Electrical physics

Every object around you is made up of charged particles. When these particles move relative to one another, you experience a phenomenon known as 'electricity'. Generating and transferring electrical energy is integral to the modern lifestyle; it is needed to light homes, power devices and charge cars, for example. And as the importance of sustainability increases, scientists and engineers must understand the efficiency of electrical systems. This chapter looks at fundamental concepts that scientists have developed to explain electrical phenomena, such as current, voltage and power. This will provide the foundation for studying practical electrical circuits in the following chapter.

Syllabus subject matter

CURRENT, POTENTIAL DIFFERENCE AND ENERGY FLOW

- Describe electric charge as positive or negative. **4.1**
- Describe electric current as carried by discrete electric charge carriers. **4.3**
- Describe the law of conservation of electric charge. **4.1**
- Explain that electric charge is conserved at all points in an electrical circuit. **4.1, 4.3**
- Describe the concepts of electrical potential difference, and power within a circuit. **4.2, 4.6**
- Solve problems involving electric current, electric charge and time using $I = \frac{q}{t}$. **4.3**
- Explain that the energy inputs in a circuit equal the sum of energy output from loads in the circuit. **4.3**
- Explain that the energy available to electric charges moving in an electrical circuit is measured using electrical potential difference. **4.2**
- Solve problems involving electrical potential difference using $V = \frac{W}{q}$. **4.2**
- Explain in qualitative terms why electric charge separation produces an electrical potential difference. **4.2**
- Solve problems involving power using $P = \frac{W}{t}$. **4.6**
- Describe the concept of resistance. **4.4**
- Solve problems using $V = IR$. **4.5**
- Discuss the differences between ohmic and non-ohmic resistors. **4.5**
- Interpret experimental data to determine the resistance across an ohmic resistor. **4.5**

CIRCUIT ANALYSIS AND DESIGN

- Describe the concept of power dissipation over resistors in a circuit. **4.6**

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4.1 Charge and the atom

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall charges of subatomic particles
- define electric charge
- recall that charge is measured in coulombs
- describe electric charge as either positive or negative
- describe the law of conservation of charge
- describe conductors as charge carriers.

All matter in the universe is made of tiny particles. These particles have a property called charge that can be positive, negative or neutral. Usually, the numbers of positive and negative charges balance out perfectly and you are unaware of them. However, when significant numbers of these charged particles become separated or move relative to each other, it results in **electricity**. To understand electricity, it is important to understand the way charged particles interact with each other.

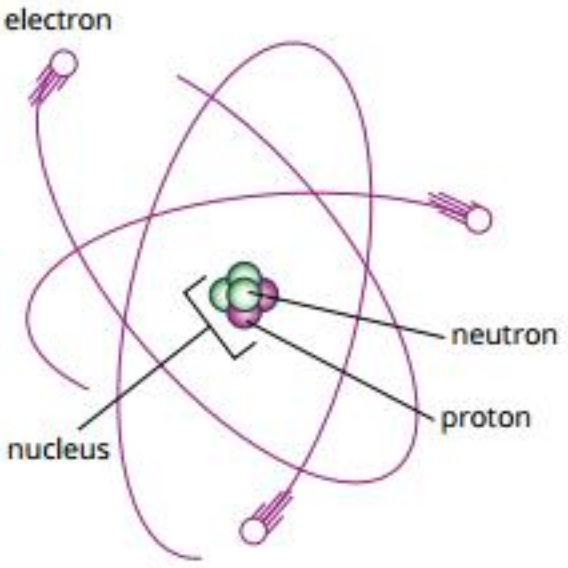


FIGURE 4.1.1 A simple model of the atom

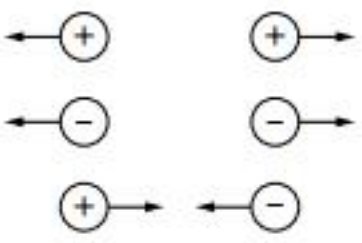


FIGURE 4.1.2 Like charges repel each other, but particles with opposite charges are attracted.

ELECTRIC CHARGE

Electric **charge** is a fundamental property of many subatomic particles. Electric charge can either be positive or negative. The size of the charge determines the force with which a particle can attract or repel other charged particles when close together. Charge is a characteristic of matter that describes whether a particle has fewer or more electrons than protons.

Charge carriers

The tiny particles that make up all matter are called **atoms**. Every atom contains a nucleus at its centre. Recall that a nucleus is made up of positively charged particles called protons and neutral particles called neutrons. The nucleus, which is positively charged due to the protons, is surrounded by negatively charged particles called electrons.

Simple models of the atom, often called planetary models, show the electrons orbiting the nucleus much like planets orbiting the Sun (Figure 4.1.1). This is because particles with like charges repel each other, but particles with opposite charges attract each other. In an atom, the negatively charged electrons are attracted to the positively charged nucleus.

This is an important rule to remember when thinking about the interaction of charged particles. The attraction of charged particles is summarised in Figure 4.1.2.

In neutral atoms, the number of electrons is the same as the number of protons. This means that their charges balance each other out, leaving the atom electrically neutral.

It is difficult to remove a proton from the nucleus of an atom. In comparison, electrons are loosely held to their respective atoms and are relatively easy to remove.

When electrons move from one object to another, each object is said to have gained a **net charge**. The object that loses the electrons will gain a net positive charge, because it will now have more positive protons than negative electrons. The object that gains electrons will gain a net negative charge. When an atom has gained or lost electrons and the number of positive and negative charges is no longer balanced, the atom has become **ionised** or has become an **ion**.

An excess of electrons causes an object to be negatively charged, and a deficit of electrons will mean the object is positively charged.

The movement of charged particles (electrons and ions) from one area to another through a medium is commonly known as electricity.

It is a relative new discovery that the movement of electrons—rather than protons—is what creates electrical effects. So, be aware that many rules and conventions used when talking about electricity refer to electric **current** as the movement of positive charge carriers.

Measuring charge

To measure the actual amount of charge of an object, a 'natural' unit (that is, based on a universal physical constant) would be the magnitude (size) of the charge carried by one electron or one proton. This fundamental constant of charge is often referred to as the **elementary charge** and is given the symbol e. A proton therefore has a charge of $+e$ and an electron has a charge of $-e$.

The size of the elementary charge is very small. For most practical situations, it is more convenient to use a larger unit to measure charge. The SI (standard) unit of charge is known as the **coulomb** (symbol C). It is named after Charles-Augustin de Coulomb (1736–1806), who was the first scientist to measure the forces of attraction and repulsion between charges.

A coulomb is quite a large unit of charge: +1 coulomb (1 C) is equivalent to the combined charge of 6.2×10^{18} protons. Therefore, the charge on a single proton is $+1.60 \times 10^{-19}$ C. Similarly, −1 C is equivalent to the combined charge of 6.2×10^{18} electrons, meaning that the charge on a single electron is -1.60×10^{-19} C.

The amount of charge, q, is equal to the number of electrons, n_e, multiplied by the charge on one electron, $-e$ (-1.60×10^{-19} C).

i $q = n_e \times -e$
where
q is the amount of charge in coulomb (C)
n_e is the number of electrons
$-e$ is the charge on one electron (-1.60×10^{-19} C).

i The elementary charge, $+e$, of a proton is equal to 1.60×10^{-19} C.
The elementary charge, $-e$, of an electron is equal to -1.60×10^{-19} C.

Worked example 4.1.1

THE AMOUNT OF CHARGE ON A GROUP OF ELECTRONS

Calculate the charge, in coulombs, carried by 6.0 billion electrons.	
Thinking	**Working**
Express 6.0 billion in scientific notation.	1.0 billion = 10^9 6.0 billion = 6.0×10^9
Calculate the charge, q, in coulombs by multiplying the number of electrons by the charge on one electron (-1.60×10^{-19} C).	$q = n_e \times -e$ $= (6.0 \times 10^9) \times (-e)$ $= (6.0 \times 10^9) \times (-1.60 \times 10^{-19}\text{C})$ $= -9.6 \times 10^{-10}$ C

➤ Try yourself 4.1.1

THE AMOUNT OF CHARGE ON A GROUP OF ELECTRONS

Calculate the charge, in coulombs, carried by 4.0 million electrons.

Worked example 4.1.2

THE NUMBER OF ELECTRONS IN A GIVEN AMOUNT OF CHARGE

The net charge on an object is –3.0 μC. Calculate the number of extra electrons on the object.
(1 μC = 1 microcoulomb = 10^{-6} C)

Thinking	Working
Express –3.0 μC in scientific notation.	$q = -3.0\,\mu C$ $= -3.0 \times 10^{-6}\,C$
Find the number of electrons by dividing the charge on the object by the charge on an electron (-1.60×10^{-19} C).	$q = n_e \times -e$ $n_e = \frac{q}{-e}$ $= \frac{-3.0 \times 10^{-6}\,C}{-1.60 \times 10^{-19}\,C}$ $= 1.9 \times 10^{13}$ electrons

➤ Try yourself 4.1.2

THE NUMBER OF ELECTRONS IN A GIVEN AMOUNT OF CHARGE

The net charge on an object is –4.8 μC. Calculate the number of extra electrons on the object.

Conservation of charge

Electric charge cannot be created or destroyed. This means that, if an object gains electric charge from another object, then the other object must lose charge. This is known as the **law of conservation of charge**. For example, if you gain +10 μC of charge by rubbing a balloon on your head, then that balloon must gain a net –10 μC of charge.

ELECTRICAL CONDUCTORS AND INSULATORS

It is much easier to move electrons than protons. Electrons also move more freely in some materials than in others.

In **metals**, the electrons are only very slightly attracted to their respective nuclei. Metals are good **conductors** of electricity. In conductors, loosely held electrons can effectively 'jump' from one atom to another and move freely throughout the material. This can be seen in Figure 4.1.3.

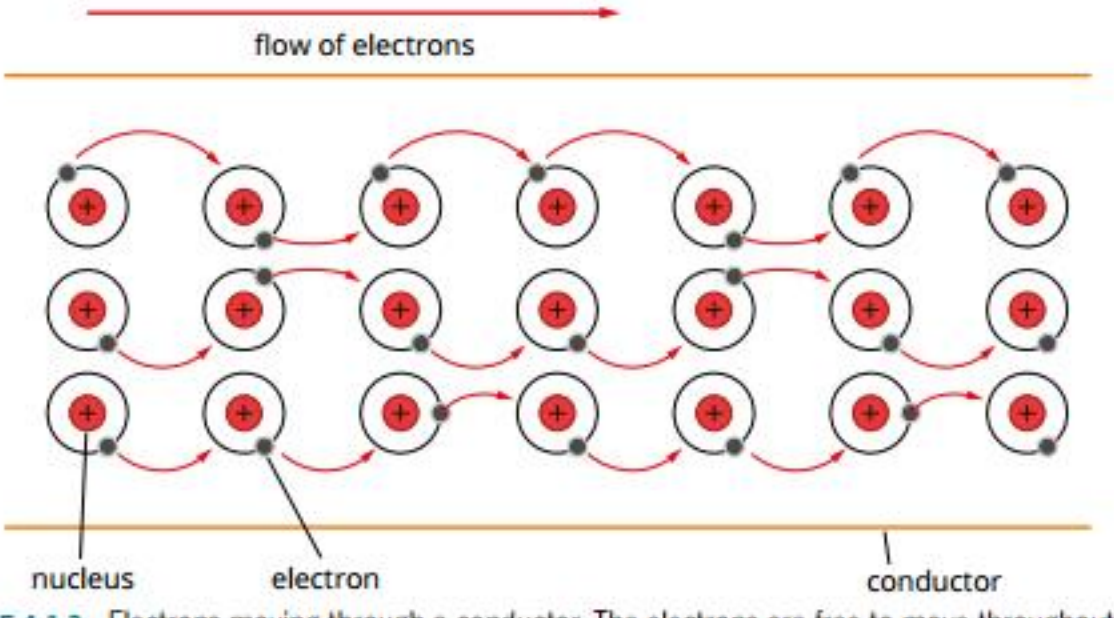


FIGURE 4.1.3 Electrons moving through a conductor. The electrons are free to move throughout the lattice of positive ions.

Copper is an example of a metal that is a good conductor. For this reason, it is used in telecommunications and electrical and electronic products (Figure 4.1.4).

In comparison, the electrons in **non-metals** are very tightly bound to their respective nuclei and cannot readily move from one atom to another. Non-metals do not conduct electricity very well and are known as **insulators**. A list of common conductors and insulators is provided in Table 4.1.1.

TABLE 4.1.1 Some common conductors and insulators

Conductors		Insulators	
Good conductors	**Moderate conductors**	**Good insulators**	**Moderate insulators**
• all metals, especially silver, gold, copper and aluminium • any ionic solution	• water • earth • semiconductors such as silicon, germanium	• plastics • polystyrene • dry air • glass • porcelain • cloth (dry)	• wood • paper • damp air • ice • snow

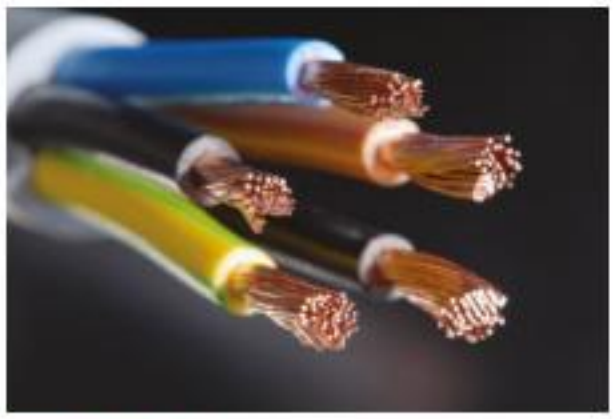


FIGURE 4.1.4 These copper wires conduct electricity by allowing the movement of charged particles.

4.1 Review

SUMMARY

- Electric charge is a fundamental property of matter. Charge can be positive or negative.
- Like charges repel; unlike charges attract.
- When an object loses electrons, it develops a positive net charge; when it gains electrons, it develops a negative net charge.
- The letter q is used to represent the amount of charge. The SI unit of charge is the coulomb (C).
- The elementary charge e, the charge on a proton, is equal to 1.60×10^{-19} C. The elementary charge $-e$, the charge on an electron, is -1.60×10^{-19} C.
- The law of conservation of charges states that electric charge cannot be created or destroyed and is always conserved. If an object gains charge from another object, the other object must lose an equal amount of charge.
- Electrons move easily through conductors, but not through insulators. This is because the electrons in materials that are good conductors are weakly attracted to the nucleus, but electrons in insulators are more strongly attracted to the nucleus.

KEY QUESTIONS

Describe

1 State the unit of measurement of charge.

2 Describe the law of conservation of charge.

Apply

3 If a material becomes negatively charged, has it lost or gained electrons?

4 Use a visual representation to demonstrate the movement of electrons in a conductor.

5 Explain why electrical circuits often consist of wires that are made from copper coated in protective rubber.

6 A metal sphere gains a net charge of $+2\,\mu C$ when in contact with a charged conducting rod.

a Determine the acquired charge of the rod.

b Describe how you calculated your answer to part a.

Analyse

7 Plastic strip A is found to attract plastic strip B. Strip C is found to repel strip B. Explain what will happen when strip A and strip C are brought close together.

8 Calculate how many electrons make up a charge of $-5.0\,C$.

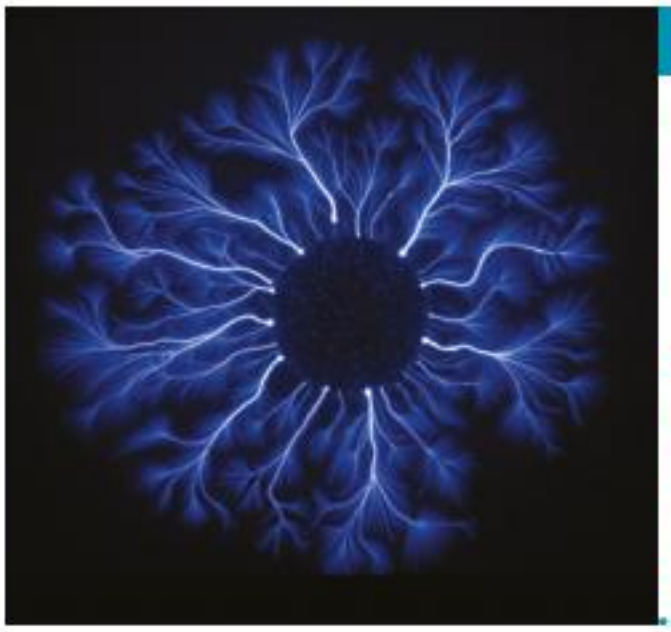
9 Calculate the charge, in coulombs, of 4.2×10^{19} protons.

10 Calculate the number of extra electrons on an object, for each of the following net charges.

a $-6.0\,\mu C$ **b** $-8.3\,C$ **c** $-1.6\,\mu C$

11 A scientist charges two identical metal spheres. Sphere A has a net charge of $+10q$. Sphere B has an overall net charge of $-4q$. The scientist then brings the spheres together so that they touch before being separated again. Determine the new net charge on each sphere.

4.2 Potential difference



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define 'potential difference' in a circuit
- explain that the energy available to charges moving in an electrical circuit is measured using potential difference
- describe the flow of current due to electrical potential difference between two points on a conductor
- recall that potential difference is measured in volts
- explain why charge separation produces an electrical potential difference
- recall that voltage is measured using a voltmeter
- recall the formula for calculating potential difference
- calculate potential difference.

Electrons will not move around a circuit unless they are provided with energy. In an electric circuit, this energy is provided by an electrochemical cell, a battery (Figure 4.2.1) or other power source.

An electrochemical cell stores chemical potential energy. Each cell has a positive and a negative terminal, often indicated by a plus (+) and minus (−) symbol, respectively. At the negative terminal (anode), chemical reactions release electrons. At the positive terminal (cathode), chemical reactions accept electrons. This flow of electrons through an external circuit is what provides electrical energy.

When a circuit connects the two ends of a cell, the chemical potential energy of the cell is transformed into electrical energy, causing electrons to move through the wire. This movement of electrons enables the delivery of electrical energy from the cell to a component, such as a bulb, where it is transformed into other forms of energy, such as light and heat.

A single cell generates electricity by transforming chemical potential energy to electrical potential energy. If a series of cells is added together, it is called a battery. Often a series of cells is packaged in a way that makes it look like a single device, but inside is a battery of cells connected together (Figure 4.2.2). The terms 'battery' and 'cell' can be used interchangeably as the term 'battery' is frequently used in common language to describe a cell.

FIGURE 4.2.1 Chemical energy is stored within cells or batteries.

FIGURE 4.2.2 A mobile-phone battery. The term 'battery' refers to a group of cells connected together.

ENERGY IN CIRCUITS

Chemical energy stored inside a battery is **transformed** (changed) into **electrical potential energy**. This potential energy is stored as a separation of charge between the two terminals of the battery. This can be visualised as a 'concentration' of charge at either end of the battery. One terminal (the negative terminal) has a concentration of negative charges; the other terminal (the positive terminal) has a concentration of positive charges. When the battery is connected within a device, chemical reactions will maintain this difference in charge between the two terminals for some time.

The difference in charge between the two terminals of a battery can be quantified (given a numerical value) as a difference in the electrical potential energy per unit charge. This is commonly called **potential difference**, V, and is measured in volts (V).

It is this potential difference between the terminals of the battery that provides the energy to a circuit. The energy is then **transferred** to different components in the circuit. At each component, the energy is transformed into a different type of energy. For example, a lightbulb transforms electrical energy into heat and light, and a fan transforms electrical energy into motion (kinetic energy) and heat and sound.

If you use a conductor to link two separate bodies with a potential difference, charges will flow through the conductor until the potential difference is equal to zero (Figure 4.2.3). For the same reasons, when a conductor is charged, charges will move through it until the potential difference between any two points in the conductor is equal to zero.

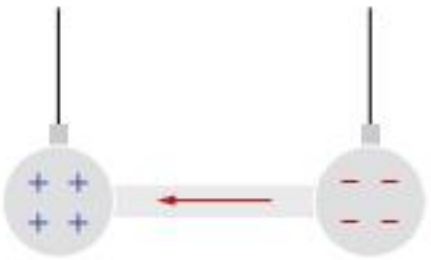


FIGURE 4.2.3 An electrical potential difference exists between these two objects due to their difference in net charge. Electrons flow from the negative object to the positive object, as shown by the arrow, until the potential difference is zero.

UNDERSTANDING POTENTIAL DIFFERENCE

When charges are separated in a battery, each charge gains electrical potential energy. In a similar way, if a mass is lifted above the ground it gains gravitational potential energy. The change in electrical potential energy of each charge is the potential difference (V).

As you can see in Figure 4.2.4, when you lift an object to some height (B) above the ground (A), you have done some work and have placed it at a height where it has more gravitational potential energy (E_g): $E_{g_B} > E_{g_A}$.

The changing potential energy of a moving mass in a gravitational field

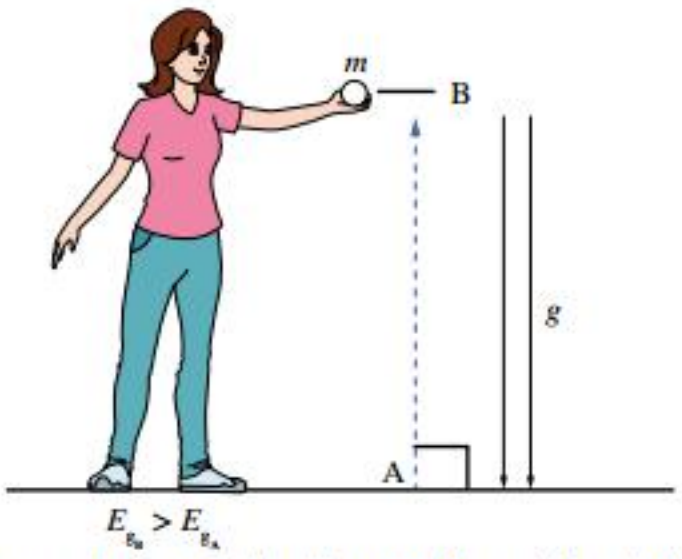


FIGURE 4.2.4 Lifting a mass above ground level increases its gravitational potential energy just as moving an electron to the negative terminal of an electric cell gives it electrical potential energy.

Volts and voltage

Somewhat confusingly, scientists use the symbol V for both the quantity potential difference *and* its unit of measurement, the volt. The context usually makes it clear which meaning is intended.

- For the potential difference variable, use italics: V.
- For the unit volts, do not use italics: V.

For this reason, potential difference is often referred to as 'voltage'.

A potential difference of $1\,JC^{-1}$ is equal to 1 V.

When a battery is labelled 9 V, this means that the battery provides 9 J of energy to each coulomb of charge.

Potential difference describes the amount of energy per unit charge being transformed from electrical energy into another form (such as heat and light in a lightbulb).

MEASURING POTENTIAL DIFFERENCE: VOLTAGE

As with other forms of energy, it is useful to measure the amount of potential difference in a given situation. Potential difference, V, is formally defined as the amount of electrical potential energy, W, given to each coulomb of charge, q. As an equation, it is:

$$V = \frac{W}{q}$$

Energy is measured in joules and charge in coulombs, so the potential difference is measured in joules per coulomb (JC^{-1}). This quantity has been assigned a unit, the **volt** (V). As work is done when energy is transformed from electrical energy into other forms (such as heat and light), the electrical potential energy is given the symbol for work, W.

Worked example 4.2.1

DEFINITION OF POTENTIAL DIFFERENCE

Calculate the electrical potential energy that is carried by 5.0 C of charge at a potential difference of 10.0 V.	
Thinking	**Working**
Recall the definition of potential difference.	$V = \frac{W}{q}$
Rearrange this to make energy the subject.	$W = Vq$
Substitute in the appropriate values and solve.	$= 10.0 \times 5.0$ $= 50\,J$

➤ Try yourself 4.2.1

DEFINITION OF POTENTIAL DIFFERENCE

A car battery can provide 3600 C charge at 12 V. Calculate the electrical potential energy that is stored in the battery.

Birds on a wire

Birds can sit on power lines without getting electrocuted even though the wires are not insulated. For current to flow through a bird on a wire, there must be a potential difference between its two feet. Since both feet are touching the same wire, which may be at a high potential (voltage), there is no potential difference between them. However, if the bird were to touch another object, such as the ground or another wire, it would experience a large electric shock. This is because there would be a potential difference between the wire and the other object, causing current to flow through the bird.

FIGURE 4.2.5 There is no potential difference between each bird's feet.

Measuring voltage: the voltmeter

Voltage is usually measured by a device called a **voltmeter**. Voltmeters measure the change in voltage (potential difference) as current passes through a particular component. This means that one wire of the voltmeter is connected to the circuit before the component and the other wire is connected to the circuit after the component. This is called connecting the voltmeter 'in parallel', making a parallel circuit. Voltmeters and parallel circuits are discussed in further detail in Chapter 5.

4.2 Review

SUMMARY

- In a circuit, the energy required for charge separation is provided by a cell or battery. The chemical energy within the cell is transformed into electrical potential energy.
- Electrical potential difference measures the electrical potential energy available per unit charge.
- Potential difference (V) can be defined as the amount of electrical potential energy, W, given to each coulomb of charge, q:

$$V = \frac{W}{q}$$

- Potential difference (voltage) is measured in volts (V).
- A potential difference of $1\,J\,C^{-1}$ is equal to 1 V.
- Potential difference is measured using a voltmeter.

KEY QUESTIONS

Describe

1 Describe 'potential difference'.

2 State the formula for calculating potential difference in terms of charge and electrical potential energy.

3 Name the piece of equipment used to measure potential difference.

4 State the units and the variable used for potential difference.

Apply

5 Explain why birds do not get electrocuted when they perch on overhead power lines.

6 In a battery, one terminal (the negative terminal) has a concentration of negative charges; the other terminal (the positive terminal) has a concentration of positive charges.

a Explain how this provides energy to electric charges moving in a circuit.

b Explain how this produces an electrical potential difference.

7 What are the similarities between gravitational potential energy and electrical potential energy?

8 Determine the conditions under which charge will flow between two bodies linked by a rod.

Analyse

9 You are working with charged metal spheres in the science laboratory. You accidentally knock your finger against one of the spheres and get a small electric shock. Describe what has occurred in terms of potential difference.

10 Calculate the amount of electrical potential energy carried by 10.0 C of charge at a potential of 20.0 V.

11 Calculate the energy provided by a 12.0 V battery that gives a charge of 10.0 C.

12 Determine how much charge must have flowed through a 12.0 V car battery if 2.00 kJ of energy was delivered to the starter motor.

4.3 Electric current

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe electric current as carried by discrete charge carriers
- distinguish between electron flow and conventional current
- describe the flow of current due to electrical potential difference between two points on a conductor
- describe the formula to calculate current
- recall that current is measured using an ammeter
- solve problems involving current, charge and time.

FIGURE 4.3.1 Electrical circuits are responsible for lighting up whole cities.

A flow of electric charge is called electric current. Current can be carried by moving electrons in a wire or by ions in solution. This section explores current as it flows through wires in electrical circuits.

Electrical circuits are involved in much of the technology used every day and are responsible for many familiar sights, such as a city skyline at night (Figure 4.3.1).

ELECTRICAL CIRCUITS

An **electrical circuit** is a path made of conductive material through which charges can flow in a closed loop. This flow of charges is called an electric current. The most common conductors used in circuits are metals, such as copper wire. The charges that flow around the circuit in the wire are negatively charged electrons. The movement of electrons in the wire is called **electron flow**.

A simple example of an electrical circuit is shown in Figure 4.3.2. The lightbulb is in contact with the positive terminal (end) of the battery and a copper wire joins the negative terminal of the battery to one end of the filament in the lightbulb. This arrangement forms a closed loop that allows electrons within the circuit to flow from the negative terminal towards the positive terminal of the battery. The battery is a source of energy. The lightbulb transforms this energy into other forms of energy, such as heat and light, when the circuit is connected.

If a switch is added to the circuit in Figure 4.3.2, the lightbulb can be turned off and on. A switch on a power point or an appliance allows you to break the circuit.

When the switch is closed, the circuit is complete. The current flows in a loop along a path made by the conductors and then returns to the battery.

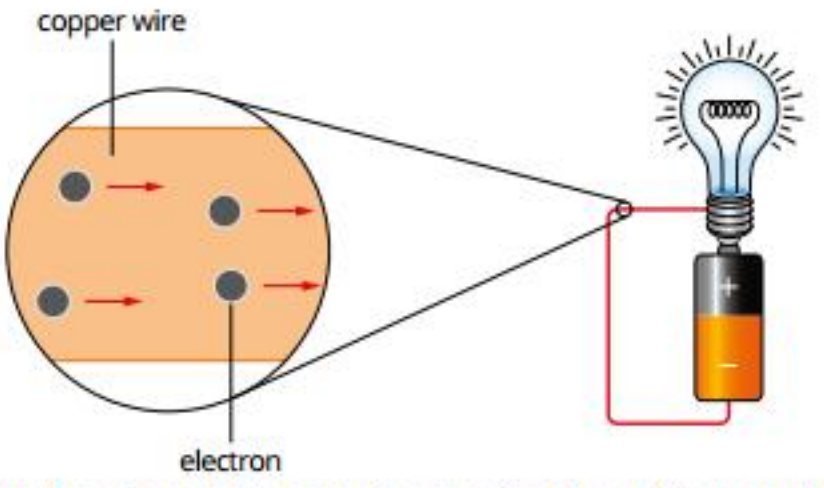


FIGURE 4.3.2 When there is a complete conduction path from the positive terminal of a battery to the negative terminal, a current flows.

When the switch is open, the circuit is broken and the current can no longer flow. This is what happens when you turn off the switch for a lamp or TV. A break in the circuit occurs when two conductors in the switch are no longer in contact. This stops the flow of current and the appliance will not work. A circuit with a broken conducting path is often called an open circuit.

Electrical circuits are discussed in more detail in Chapter 5.

> **i** Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.

Electron flow

In any piece of conducting material, such as copper wire, 'free' electrons (free to move) are present throughout the material. If there is no current flowing, this means there is no net flow of electrons, but the electrons are still present.

When you connect a piece of conducting material to the negative terminal of a battery, the negative terminal tries to 'push' the electrons away. However, the electrons will not flow if the circuit is open. This is because the electrons at the open part of the circuit have effectively reached a dead end, like cars stopped at a roadblock. This prevents all the other electrons in the material from flowing, like a long traffic jam caused by the roadblock.

When you close the circuit, you create a clear pathway for the electrons to flow through. This means the electron closest to the negative terminal forces the next electron to move, and so on, all the way around the circuit. Therefore, all electrons move almost simultaneously throughout the circuit so that electrical devices, such as light bulbs, seem to turn on immediately after you flick the switch.

Conventional current vs electron flow

When electric currents were first studied, it was (incorrectly) thought the charges that flowed in circuits were positive. Based on this, scientists traditionally talked about electric current as if current flowed from the positive terminal of the battery to the negative terminal. This convention is still used today, even though you know now that it is actually the negative charges (electrons) that flow around a circuit.

The direction of **conventional current** is opposite to the direction of electron flow, as shown in Figure 4.3.3. Conventional current (or current), I, flows from the positive terminal of a power supply to the negative terminal. Electron flow (or electron current) refers to the flow of electrons from the negative terminal to the positive terminal of a power supply.

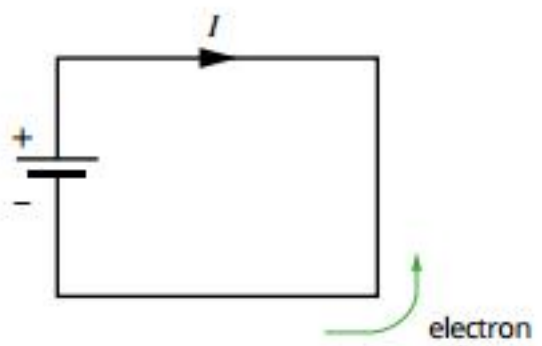


FIGURE 4.3.3 Conventional current (I) and electron flow are in opposite directions. The long line shown on the battery symbol indicates the positive terminal of the battery.

MEASURING CURRENT

One common misconception about current is that charges are used up or lost when a current flows from one point to another. However, the charge carriers (electrons) are conserved at all points. This is the law of conservation of charge.

As current flows, electrons travel into the wire at the negative terminal of the battery. As electrons flow around a circuit, they remain within the metal conductor. They flow through the circuit and return to the battery at the positive terminal—they are not lost in between. In common electrical circuits, a current consists of electrons flowing within a copper wire (Figure 4.3.3). This current, I, can be defined as the amount of charge that passes through a point in the conductor per second.

Quantifying current

The number of electrons that pass through a point in a circuit per second gives a measure of electric current. Because the electrons do not leave the wire, current is conserved in all parts of a circuit. Current is measured in **amperes**, or amps (A). One ampere of current is equivalent to one coulomb per second ($C\,s^{-1}$).

Note that a flow of 1 C of *positive charge to the right* in one second is equivalent to a flow of 1 C of *negative charge to the left* in one second. That is, both situations represent a conventional current of 1 A to the right. This is due to the law of conservation of charge.

The current, I, is the amount of charge, q, that flows through a point in a circuit in time, t, seconds:

$$I = \frac{q}{t}$$

Current is a flow of electrons. It is equal to the number of electrons, n_e, that flow through a particular point in the circuit multiplied by the charge on one electron, q_e, divided by the time that has elapsed in seconds, t.

$$I = \frac{q}{t} = \frac{n_e q_e}{t}$$

A typical current in a circuit powering a small DC motor would be about 50 mA. Even with this seemingly small current, approximately 3×10^{17} electrons flow past any point on the wire each second.

Electrons generally do not travel in straight lines through conductors, as they constantly collide with other particles in the medium; therefore, the average velocity at which particles travel through a conductor is used to measure current. This average is known as the **drift velocity**. The drift velocity for electrons in a copper wire is of the order of $10^{-5}\,\text{m s}^{-1}$.

Current is a measure of how fast electrons move through a point in a circuit over time:

$$I = \frac{q}{t} = \frac{n_e q_e}{t}$$

where

I is the current in amperes (A)

q is the amount of charge in coulombs (C)

n_e is the number of electrons

q_e is the charge on an electron (-1.60×10^{-19} C)

t is time in seconds (s).

Worked example 4.3.1

USING $I = \frac{q}{t}$

Calculate the number of electrons that flow past a particular point each second in a circuit that carries a current of 0.5 A.	
Thinking	**Working**
Rearrange the equation $I = \frac{q}{t}$ to make q the subject.	$q = I \times t$
Calculate the amount of charge that flows past the point in question by substituting the values given.	$q = 0.5 \times 1$ $= 0.5\,\text{C}$
Find the number of electrons by dividing the charge by the charge on an electron (1.60×10^{-19} C).	$n_e = \frac{q}{q_e}$ $= \frac{0.5}{1.60 \times 10^{-19}}$ $= 3 \times 10^{18}$ electrons

➤ Try yourself 4.3.1

USING $I = \frac{q}{t}$

Calculate the number of electrons that flow past a particular point each second in a circuit that carries a current of 0.75 A.

Measuring current: the ammeter

Current is commonly measured by a device called an **ammeter**.

An ammeter is connected along the same path taken by the current flowing through the a device such as a lightbulb. This is referred to as connecting the ammeter 'in series'. Ammeters and series circuits are covered in more detail in Chapter 5.

ANALOGIES FOR ELECTRIC CURRENT

You cannot see the movement of electrons in a wire, so it is sometimes helpful to use analogies or 'models' to visualise or explain the way an electric current behaves. It is important to remember that no analogy is perfect: it is only a representation, and there will be situations in which the electric current does not act as you would expect from the analogy.

Water model

A common model is to think of electric charges as water being pumped around a pipe system, as shown in Figure 4.3.4. In this model, the battery pushes electrons through the wires just like a pump pushes water through the pipes. Water cannot be compressed, so the same amount of water flows in every part of a pipe, just as the electric current is the same in every part of a wire. The lightbulb in an electrical circuit transforms electrical potential energy into heat and light, just like the turbine transforms the gravitational potential energy of the water into kinetic energy. The water that has flowed through the turbine flows back to the pump that provides the energy needed for it to keep flowing.

This model reinforces the following characteristics of an electric current:

- The power supply transfers energy to the electrons and so the electrons gain potential energy.
- The energy of the electrons is transformed into other types of energy when the electrons pass through the components in the circuit.

Bicycle-chain model

Although electrons move relatively slowly through a conductor, the effects are almost instantaneous. For example, the delay between flicking a light switch and the light coming on is too small to be noticed. One way of understanding this is to compare an electric current to a bicycle chain, as shown in Figure 4.3.5.

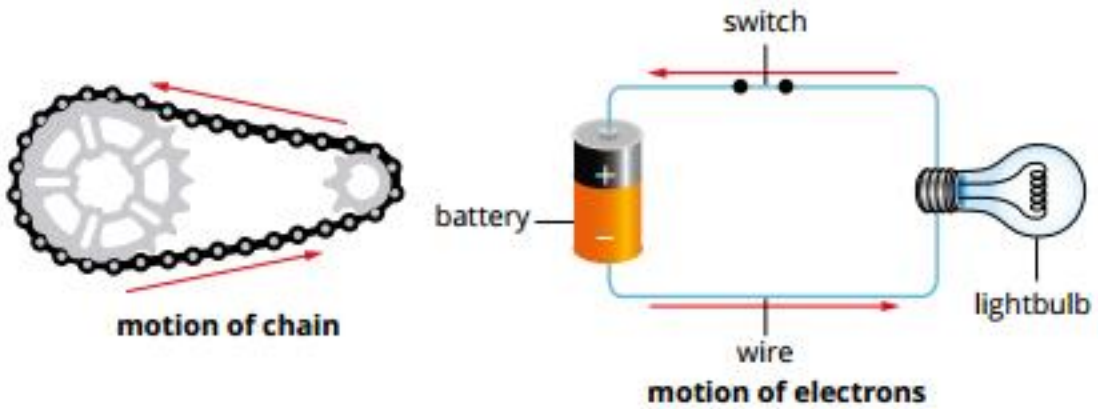


FIGURE 4.3.5 Electrons in a wire are like the links of a bicycle chain. Just like the links of a bicycle chain, electrons move together in a conductor.

A wire is full of electrons that all repel each other, so moving one electron affects all the others around it. An electric current is like a bicycle chain: even if the cyclist pedals slowly, the links in the chain mean that energy is instantly transferred from the pedals to the wheel. In this model, the pedals of the bicycle are like the battery of the electrical circuit: the pedals provide the energy that causes the chain to move.

The bicyle-chain model reinforces the following characteristics of an electric current:

- Electric effects are nearly instantaneous, just as there is no delay between turning the pedals and the back wheel of the bicycle turning.
- Charges in an electric current are not 'consumed' or 'used up', just as links in the chain are not used up.
- The amount of energy provided by an electric current is not entirely dependent on the current. This is like when a cyclist changes gears to give the same amount of energy to the bicycle while pedalling at different rates.

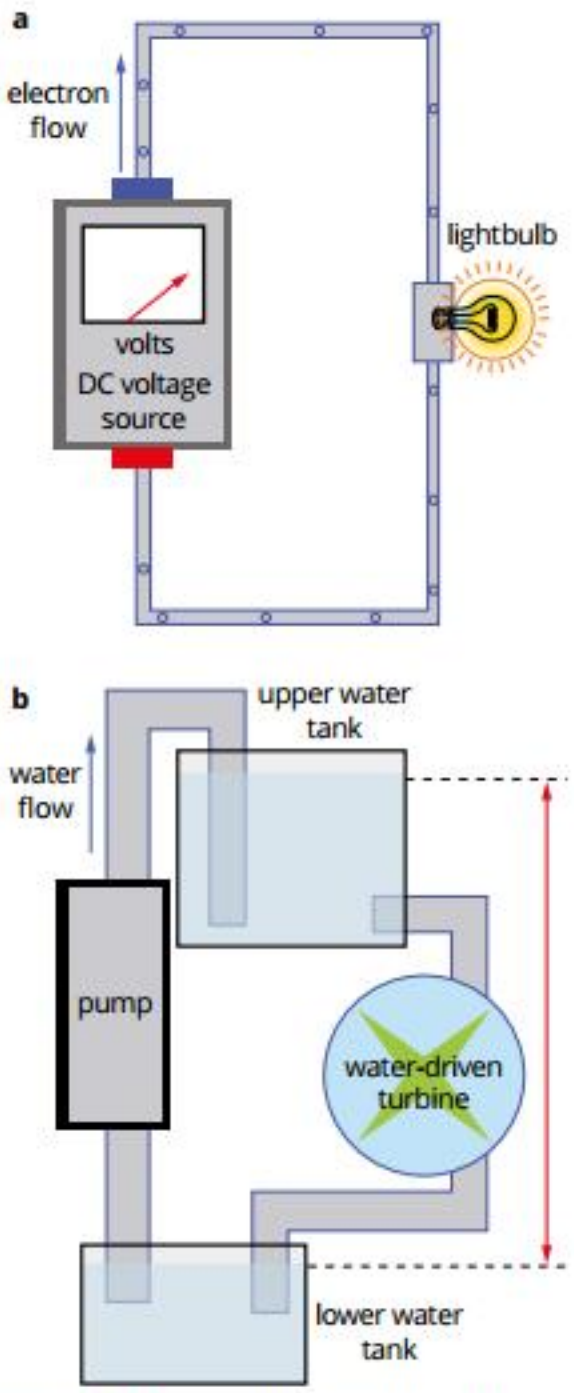


FIGURE 4.3.4 An electric current (a) can be compared to water flowing through a pipe system (b).

Although the bicycle-chain model can be a helpful analogy, there are a number of important differences between a bicycle chain and an electrical circuit.

- The number of charges flowing in an electric current is much larger than the number of links in a bicycle chain.
- Electrons in a wire do not touch one another like the links in a chain.

ANALOGIES FOR POTENTIAL DIFFERENCE

The two models used for electric current can also be used to understand the concept of potential difference, which was covered in the Module 4.2.

In the water model shown in Figure 4.3.4, potential difference is similar to the water pressure in the pipe. If the water is pumped into a raised water tank, then the potential difference can also be compared to the gravitational potential energy given to each drop of water.

In the bicycle-chain model shown in Figure 4.3.5, potential difference is related to how hard the bicycle is being pedalled. If the cyclist is pedalling hard, this would correspond to a high voltage in which each link in the chain is carrying a larger amount of energy than if the cyclist was pedalling slowly.

In both analogies, the overall rate of energy output (power) is related to both the current and the potential difference. In the water model, the pressure in the pipe could be very high but the rate of energy transfer will depend on how quickly the water is flowing. Similarly, a cyclist can work at the same rate by pedalling hard with the chain moving slowly or pedalling more easily but with the chain moving more quickly.

4.3 Review

SUMMARY

- A flow of electric charge (electrons) is called electric current.
- Current will flow between two points on a conductor if there is an electrical potential difference between those points.
- Electric current is carried by discrete charge carriers.
- Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.
- When an electric current flows, electrons all around the circuit move towards the positive terminal, at the same time. This is called electron flow.
- Conventional current in a circuit flows from the positive terminal to the negative terminal.
- Current is dependent on the speed of charged particles, the number of charged particles that are moving and the charge being carried by the particles.
- Current, I, is defined as the amount of charge, q, that passes through a point in a conducting wire per second. It has the unit amperes or amps (A), which are equivalent to coulombs per second. The equation for this is:

$$I = \frac{q}{t} = \frac{n_e q_e}{t}$$

- Current is measured with an ammeter connected along the same path as the current flowing (that is, in series) within the circuit.

KEY QUESTIONS

Describe

1 State what the links in the bicycle chain can be compared with in the bicycle-chain model for electric current.

2 State the formula for determining electric current.

3 Describe 'drift velocity'.

4 Name a common conductor used in circuits.

5 Name the equipment used to measure current.

6 Identify the charge carriers in conventional current.

Apply

7 Describe the requirements for current to flow in a circuit.

8 Describe the direction of electron flow in an electric circuit.

9 A scientist charges two metal spheres so that they have net charges of –1 C and +1 C, respectively. The scientist then connects the two spheres with a conducting rod. Describe how this will produce an electric current.

10 Determine the equation for the number of electrons passing a point in a circuit with a given current, *I*.

11 Why does a light turn off when you flick the light switch to 'off'?

Analyse

12 Differentiate between conventional current and electron flow.

13 When a lightbulb is connected in an electrical circuit, it uses electrical energy to produce heat and light. Explain whether this means that charges are used up as they flow through the circuit.

14 Max connects a simple electrical circuit, and notices that when the switch is closed, the lightbulb lights up immediately. He says this is because the electrons move around the circuit at the speed of light. Consider whether he is correct.

15 A car headlight draws a current of 5.0 A. Determine how much charge will have flowed through it in each of the following times.

- **a** 1.0 second
- **b** 1.0 minute
- **c** 1.0 hour

16 In a solution of salt water, a total positive charge of +15 C moved past a point to the right in 5.0 s, and in the same time a total negative charge of –30.0 C moved to the left.

- **a** Determine the current through the solution during this time.
- **b** Later, it was found that in 5.0 s a total of +5.0 C had moved to the right while –15 C had moved to the left. Determine the current this time.

17 Exactly 10^{20} electrons flow past a point in 4.0 seconds.

- **a** Calculate the amount of charge, in coulombs, that moves past a point in this time.
- **b** Determine the current, in amps.

18 3.2 C flows past a point in 10.0 seconds.

- **a** Calculate the number of electrons that move past a point in this time.
- **b** Determine the current in amps.

4.4 Resistance

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that resistance is measured in ohms
- describe the concept of resistance
- recall how resistance is dependent on the material of a conductor, proportional to length and inversely proportional to cross-sectional length.

Resistance is an important concept because it links the ideas of potential difference and current. **Resistance** is a measure of how hard it is for current to flow through a particular material. As conductors allow current to pass through easily, they are said to have low resistance. Insulators have a high resistance because they 'resist' or limit the flow of charges through them.

For a particular object or material, the amount of resistance can be quantified (given a numerical value). This means that the performance of electrical circuits can be studied and predicted with a high degree of confidence.

Resistance is a measure of how hard it is for current to flow through a particular material. Resistance is measured in ohms (Ω).

RESISTANCE TO THE FLOW OF CHARGE

Energy is required to create and maintain an electric current. For electrons to move from one place to another, they need to first be separated from their atoms and then given energy to move. In some materials (conductors), the amount of energy required for this is negligible (almost zero). In insulators, a much larger amount of energy is required.

When the electrons are moving through the material, energy is also required to keep them moving at a constant speed. Consider an electron travelling through a piece of copper wire. It is common to imagine the wire as an empty pipe or hose through which electrons flow. However, a piece of copper wire is not empty; it is full of copper ions. These ions are packed tightly together in a lattice arrangement. As an electron moves through the wire, it will 'bump' into the ions. The electron needs constant 'energy boosts' to keep it moving in the right direction. This is why an electrical device will stop working as soon as the energy source (such as a battery) is disconnected.

Electron movement

Even when current is not flowing, free electrons tend to move around in a piece of metal due to thermal effects. The free electrons are rushing around at random with great speed. However, the net velocity of an electron through a wire—the drift velocity introduced in Module 4.3—is quite slow. Figure 4.4.1 compares the random motion of an electron when current is not flowing (AB) to the motion of the electron when current is flowing (AC). The difference between the two paths is only small. However, the combined effect of countless electrons moving together in this way represents a significant net movement of charge.

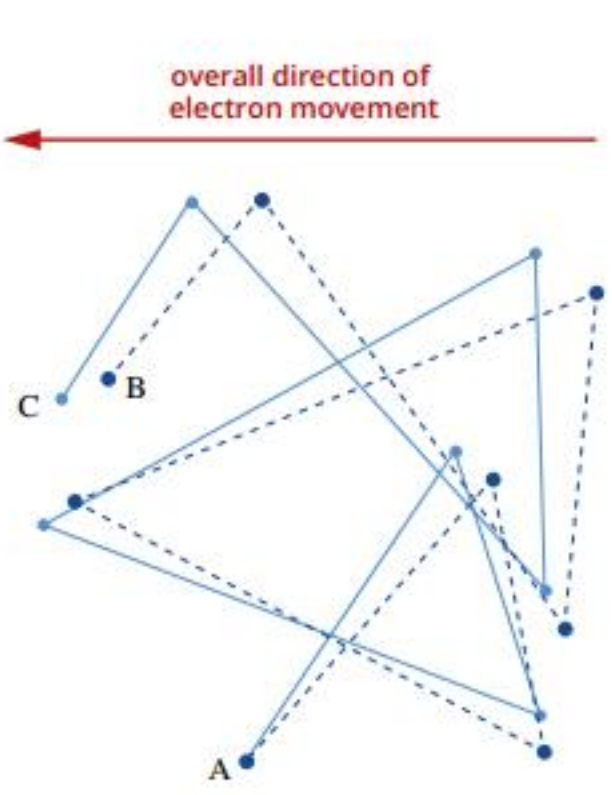


FIGURE 4.4.1 Path AB shows the random motion of an electron due to thermal effects. Path AC shows the path of the same electron when an electric current is flowing in the direction indicated.

VARIABLES THAT AFFECT RESISTANCE

Understanding the way electrons move through a wire can help us to make some predictions about the resistance of different objects.

Cross-sectional area and length

Consider electrons moving through two pieces of wire: one long and one short. In the longer piece of wire, the electrons bump into more ions along the way, so more energy would be needed for the electrons to travel from one end to the other. In other words, the longer piece of wire would provide greater 'resistance' to the flow of electric current.

Similarly, a thicker piece of wire allows more electrons to flow through it at the same time, much like a dual-lane highway allows faster traffic flow than a single lane. In practice, the cross-sectional area of the wire (its area when viewed end on) is important. The greater the cross-sectional area of the wire, the lower its resistance will be.

The relationship between the resistance of a conductor and its length and thickness follows a mathematical relationship. There is a direct relationship between resistance and length: doubling the length of the conductor doubles its resistance. There is an inverse relationship between resistance and the cross-sectional area of the conductor.

Temperature

Another factor that affects the resistance of a material is its temperature. The temperature of an object is a measure of the average kinetic energy of its particles. The temperature of a solid is an indication of how quickly its particles are vibrating.

Increasing the temperature of a piece of copper wire means that the copper ions will vibrate back and forth more quickly. This makes it more likely that an electron will collide with the ion as it moves past it. Therefore, increasing the temperature of the wire also increases the resistance of the wire.

Similarly, current passing through a conductor can cause it to heat up. Think again of an electron moving through a copper wire: when the electron collides with a copper ion, it transfers some of its kinetic energy to the ion. As a result of this collision, the copper ion gains kinetic energy, causing it to vibrate more quickly. An increase in the kinetic energy of the copper means that its temperature has increased, so the copper wire heats up.

This is one of the reasons why personal computers contain cooling fans or heatsinks, as shown in Figure 4.4.2. Electrical components are packed very tightly together on the computer motherboard. Removing heat from the components and the conductors that connect them prevents the computer from overheating. It also reduces the resistance of the components and helps them to run more efficiently.

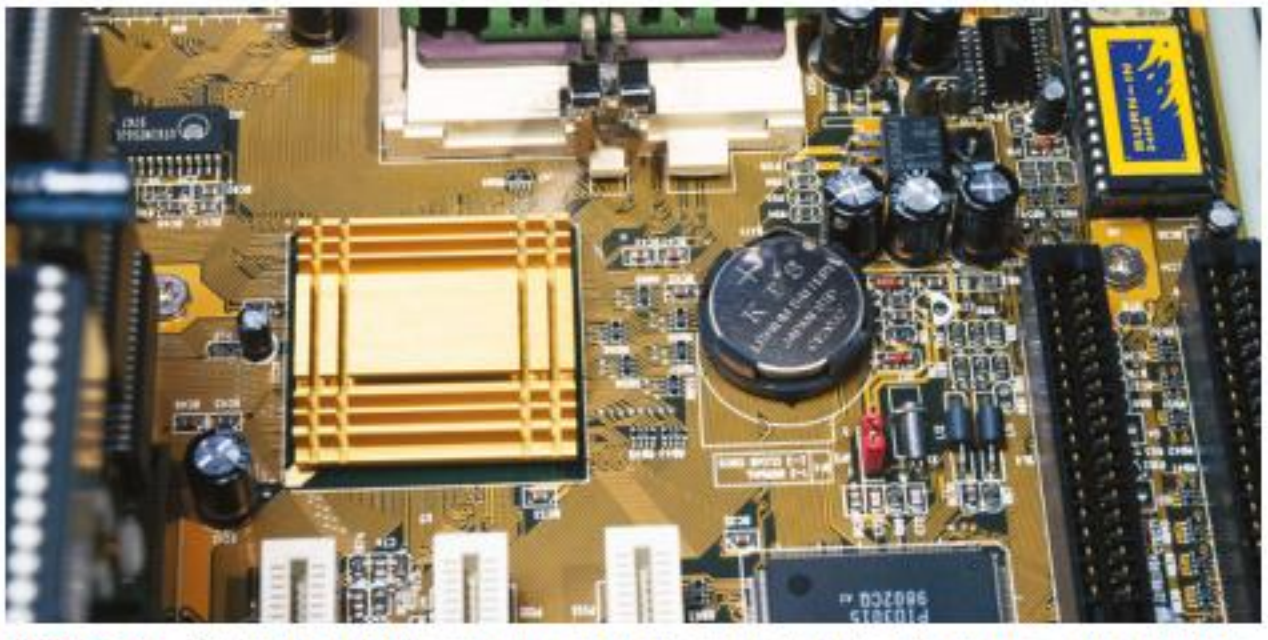


FIGURE 4.4.2 The heatsink in this computer motherboard conducts heat from surrounding electrical components and dissipates it to cool them down.

RESISTORS IN SIMPLE CIRCUITS

Resistors are often used to control the amount of current in a particular circuit. Resistors can be manufactured to produce a relatively constant resistance over a range of temperatures. A colour-coding system is used on resistors to explain the amount of resistance they provide, including a percentage tolerance (precision). Figure 4.4.3 shows a resistor that uses the colour-coding system.

FIGURE 4.4.3 Common resistors are electrical devices with a known resistance. The coloured bands indicate the resistor's resistance and tolerance.

4.4 Review

SUMMARY

- Resistance is a measure of how hard it is for current to flow through a particular material.
- Resistance is measured in ohms (Ω).
- The resistance of a material is proportional to its length and temperature and is inversely proportional to its cross-sectional area.

KEY QUESTIONS

Describe

1 Describe 'resistance'.

2 State the standard unit of measurement for resistance.

3 State three variables that affect resistance in a wire.

Apply

4 Identify which has a higher resistance: copper or rubber. Justify your response.

5 The colour-coding system on resistors provides information about the amount of resistance that the resistor provides and its percentage tolerance. What does the percentage tolerance of a resistor tell you?

Analyse

6 Two pieces of conducting wire are connected to the same amount of potential difference. The electron flow in wire 1 is found to be lower than in wire 2. Describe the resistance of the two wires.

7 **a** If the length of a piece of wire is increased, would its resistance increase or decrease?

b If the cross-sectional area of a piece of wire is increased, would its resistance increase or decrease?

c The resistance of a piece of wire is found to be 0.8Ω. Determine the resistance of a piece of the same wire twice as long.

8 Assess why the resistance of a wire would increase as it heats up.

4.5 Ohm's law

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall Ohm's law, $V = IR$
- solve problems using Ohm's law
- recall properties of ohmic conductors
- discuss the differences between ohmic and non-ohmic conductors
- interpret experimental data to determine the resistance across an ohmic conductor
- investigate resistance across ohmic conductors.

As discussed in Module 4.4, the resistance of a component is a measure of how difficult it is for electric charge to flow through the component (such as a lightbulb). This resistance is caused by collisions between charge carriers (electrons) and other charge carriers and the fixed positive metal ions in a circuit.

Georg Ohm (1789–1854) discovered that if the temperature of a metal wire was kept constant, the current flowing through it was directly proportional to the potential difference across it: $I \propto V$. This relationship would later be known as Ohm's law.

Ohm's law states that the potential difference across a metallic conductor, V, and the current flowing through it, I, are proportional at a given temperature. For example, if the potential difference across a wire is doubled, then the current flowing through the wire would also double. If the potential difference is tripled, then the current would also triple. In Ohm's law, R is the proportionality constant (resistance) in ohms (Ω).

$$V = IR \text{ or } \Delta V = IR$$

This equation can be transposed to give a quantitative (mathematical) definition for resistance: $R = \frac{V}{I}$

The relationship $V = IR$ should only be called Ohm's law when the resistance of a conductor is constant for any value of V or I. However, this relationship is commonly known as Ohm's law for values of R that vary too.

If an identical voltage produces two different-sized currents when separately connected to two light bulbs, then the resistance of the two light bulbs must differ. A higher current would mean a lower resistance of the lightbulb, according to Ohm's law. This is because, when a conductor provides less resistance, more current can flow.

Ohm's law:

$V = IR$

where

V is the potential difference in volts (V)

I is current in amps (A)

R is the constant of proportionality (resistance) in ohms (Ω).

Worked example 4.5.1

USING OHM'S LAW TO CALCULATE RESISTANCE

When a potential difference of 3.0 V is applied across a piece of wire, 5.0 A of current flows through it. Calculate the resistance of the wire.	
Thinking	**Working**
Recall Ohm's law.	$V = IR$
Rearrange the equation to make R the subject.	$R = \frac{V}{I}$
Substitute in the values for this situation and solve.	$R = \frac{3.0}{5.0}$ $= 0.60\,\Omega$

➤ Try yourself 4.5.1

USING OHM'S LAW TO CALCULATE RESISTANCE

An electric bar heater draws 10.0A of current when connected to a 240.0V power supply. Calculate the resistance of the element in the heater.

Ohm's law can also be used to determine the current flowing through a resistor when a particular potential difference is applied across it. Similarly, if the current and resistance are known, the potential difference across the resistor can be calculated.

Worked example 4.5.2

USING OHM'S LAW TO FIND CURRENT

A 100Ω resistor is connected to a 12V battery. Calculate the current (in mA) that would flow through the resistor.

Thinking	Working
Recall Ohm's law.	$V = IR$
Rearrange the equation to make I the subject.	$I = \frac{V}{R}$
Substitute in the values for this problem and solve.	$I = \frac{12}{100} = 0.12\,\text{A}$
Convert the answer to the required units.	$I = 0.12\,\text{A}$ $= 0.12 \times 10^3\,\text{mA}$ $= 120\,\text{mA}$

➤ Try yourself 4.5.2

USING OHM'S LAW TO FIND CURRENT

The element of a bar heater has a resistance of 25Ω. Calculate the current (in mA) that would flow through this element if it is connected to a 240V supply.

Worked example 4.5.3

USING OHM'S LAW TO FIND POTENTIAL DIFFERENCE

A current of 0.25A flows through a 22Ω resistor. Calculate the voltage across the resistor.

Thinking	Working
Recall Ohm's law.	$V = IR$
Substitute in the values for this problem and solve.	$V = 0.25 \times 22$ $= 5.5\,\text{V}$

➤ Try yourself 4.5.3

USING OHM'S LAW TO FIND POTENTIAL DIFFERENCE

The globe of a torch has a resistance of 5.7Ω when it draws 700.0mA of current. Calculate the potential difference across the globe.

OHMIC AND NON-OHMIC CONDUCTORS

Conductors that obey Ohm's law—that is, conductors that have a constant resistance—are known as **ohmic** conductors. Resistors are ohmic conductors because the current flowing through a resistor is usually proportional to the voltage across the resistor.

You can identify an ohmic conductor by measuring the current that flows through the conductor when different potential differences are applied across it. If the relationship between the measured current and potential difference obeys Ohm's law (that is, $V \propto I$), then it is an ohmic conductor.

Worked example 4.5.4

IDENTIFYING OHMIC CONDUCTORS FROM DATA

The table below shows measurements for the potential difference and corresponding current across a conductor.

***V* (V)**	0	2	4	6
***I* (A)**	0	0.25	0.50	0.75

From the available data, determine if the conductor is ohmic.

Thinking	Working
Recall the definition of resistance according to Ohm's law.	$R = \frac{V}{I}$
Determine the constant of proportionality, the resistance, for each column.	Column 2 $R = \frac{V}{I}$ $= \frac{2}{0.25}$ $= 8\Omega$ Column 3 $R = \frac{V}{I}$ $= \frac{4}{0.50}$ $= 8\Omega$ Column 4 $R = \frac{V}{I}$ $= \frac{6}{0.75}$ $= 8\Omega$
Determine if the conductor is ohmic. For a conductor to be an ohmic conductor it must obey Ohm's law with $R = \frac{V}{I} =$ constant, i.e. $V \propto I$.	The resistance is constant across the available data, so the conductor is ohmic.

➤ Try yourself 4.5.4

IDENTIFYING OHMIC CONDUCTORS FROM DATA

The table below shows measurements for the potential difference and corresponding current for an ohmic conductor.

***V* (V)**	0	3	9	12
***I* (A)**	0	0.20	0.60	0.80

From the available data, determine if the conductor is ohmic.

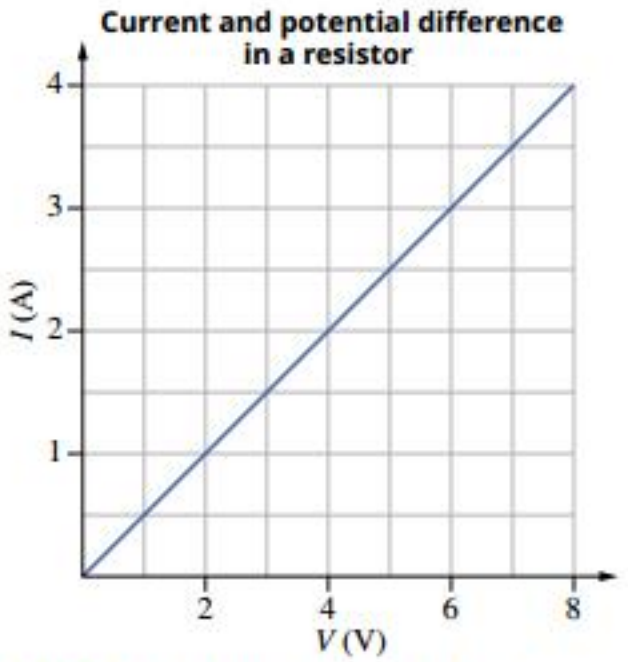
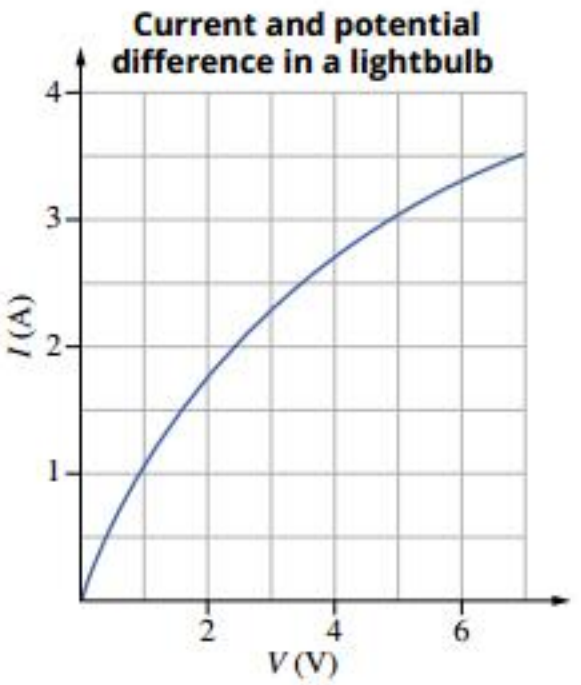


FIGURE 4.5.1 The resistance of an ohmic conductor is constant, so the *I*–*V* graph is a straight line that passes through the origin.



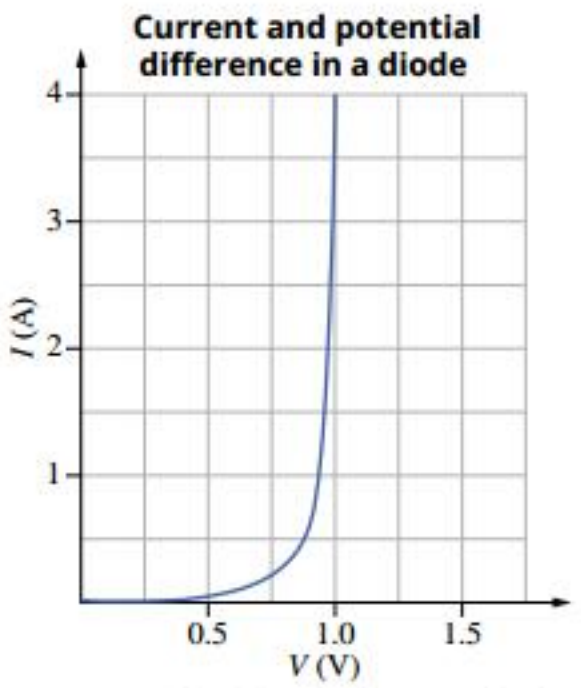


FIGURE 4.5.2 The *I*–*V* graph for a non-ohmic resistor is not a straight line.

The data from an experiment in which the current and potential difference are measured for a device is usually plotted on an *I*–*V* graph. If the conductor is ohmic, this graph will be a straight line passing through the origin (Figure 4.5.1).

The resistance of the ohmic conductor (or resistor) can be found from the gradient of the *I*–*V* graph. Ohm recognised that the gradient was equal to the inverse of the resistance:

$$\text{gradient} = \frac{1}{R} = \frac{\text{rise}}{\text{run}} = \frac{4-1}{8-2} = \frac{3}{6}$$

$$R = \frac{6}{3} = 2\,\Omega$$

However, not all conductors are ohmic. The *I*–*V* graphs for **non-ohmic** conductors are not straight lines (Figure 4.5.2). Light bulbs and diodes are examples of non-ohmic conductors.

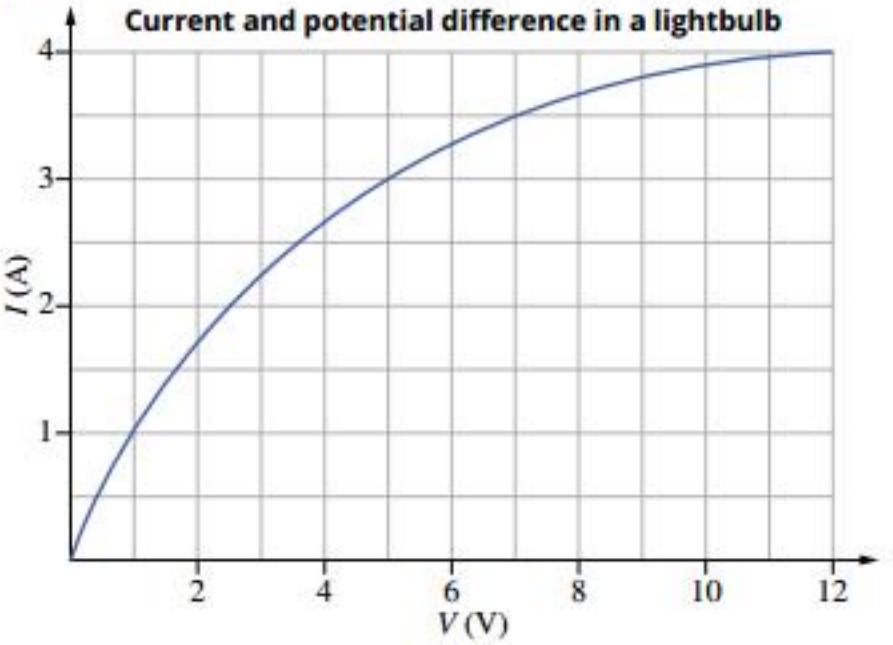
USING *I*–*V* GRAPHS TO DETERMINE RESISTANCE

For an ohmic conductor, the resistance will be a constant regardless of the potential difference across the conductor. This will result in a straight-line graph where the gradient is equal to $\frac{I}{R}$. However, the resistance of a non-ohmic conductor will vary. The resistance of a non-ohmic conductor for a particular potential difference can be found by reading the value of the current from the *I*–*V* graph and using $R = \frac{V}{I}$. Remember, this relationship is only called Ohm's law when the resistance of a conductor is constant, but the relationship can be used for non-ohmic conductors. It is not necessary (or correct) to find the gradient of the tangent to the curve, even though this is a common technique in other areas of physics.

Worked example 4.5.5

CALCULATING RESISTANCE FOR A NON-OHMIC CONDUCTOR

Calculate the resistance of the lightbulb with the *I*–*V* graph below, when the potential difference is 5.0 V.

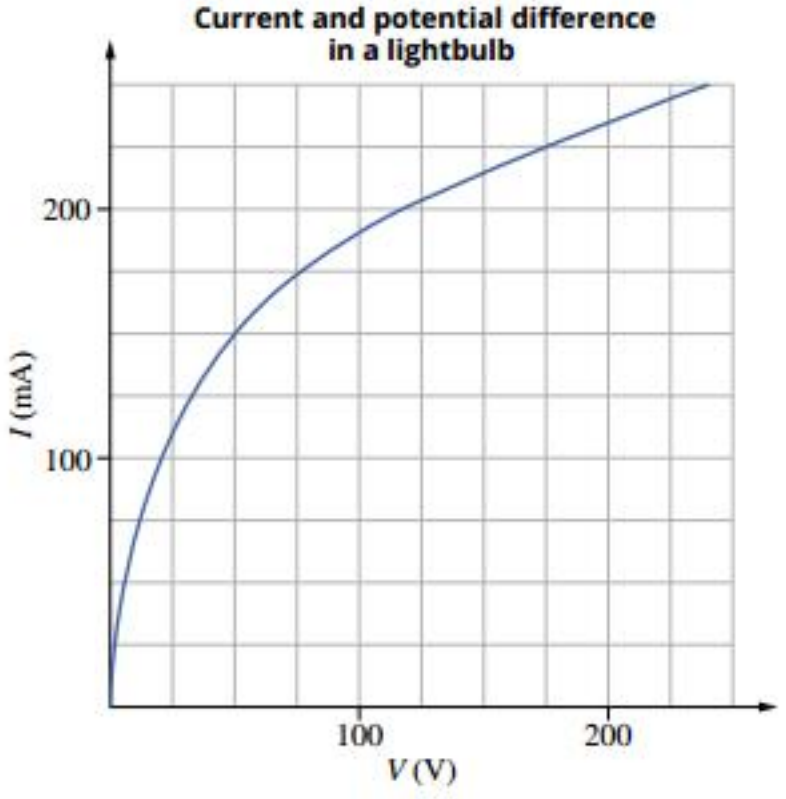


Thinking	Working
From the graph, determine the current at the required potential difference.	For $V = 5.0$ V, $I = 3.0$ A
Substitute these values into Ohm's law to find the resistance.	$R = \frac{V}{I}$ $= \frac{5.0}{3.0}$ $= 1.7\,\Omega$

➤ Try yourself 4.5.5

CALCULATING RESISTANCE FOR A NON-OHMIC CONDUCTOR

A 240V, 60W incandescent lightbulb has *I–V* characteristics shown in the graph below. Calculate the resistance of the lightbulb at 175V.



4.5 Review

SUMMARY

- Ohm's law describes the relationship between current, potential difference and resistance:

$$V = IR$$

- Conductors that obey Ohm's law are known as ohmic conductors.
- Ohmic conductors have a constant resistance. The resistance of non-ohmic conductors varies for different potential differences.
- A graph of *I*–*V* can be used to find the resistance of an ohmic conductor by calculating the gradient of the line. The gradient is equal to the inverse of the resistance.

KEY QUESTIONS

Describe

1 State Ohm's law.

2 Describe an ohmic conductor.

Apply

3 A student measures the current drawn by a resistor when different values of potential difference are applied. They plot their results on a graph. Describe the shape of the graph and how the student could find the resistance of the resistor from the graph if:

a the resistor is ohmic

b the resistor is non-ohmic.

4 Sketch an *I*–*V* graph of an ohmic conductor.

5 A light-dependent resistor (LDR) changes resistance depending on the light that shines on it. Identify whether this is an ohmic or non-ohmic resistor.

6 The table below shows measurements for the potential difference and corresponding current through a conductor.

***V* (V)**	0	1	2	3
***I* (A)**	0	0.01	0.02	0.03

Determine if the conductor is ohmic or non-ohmic.

Analyse

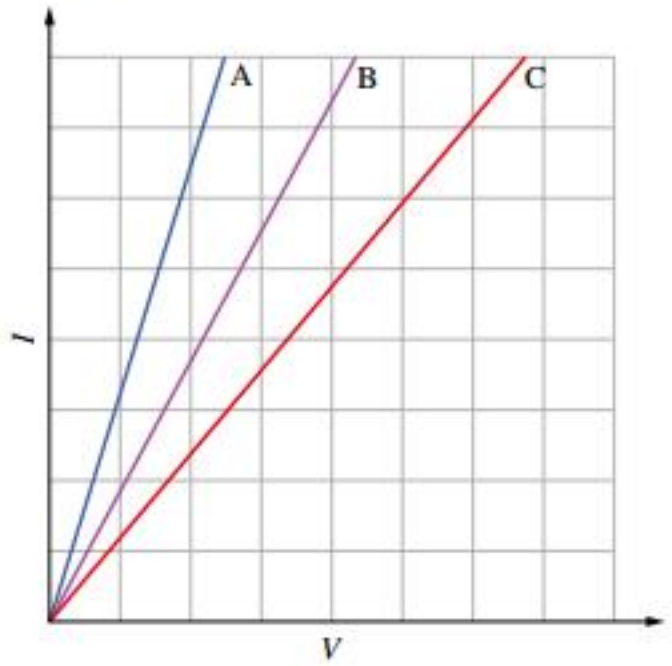
7 A student finds that the current through a resistor is 3.5 A when a voltage of 2.5 V is applied to it.

a Determine the resistance of the resistor.

b The voltage is then doubled and the current is found to increase to 7.0 A. Explain whether the resistor is ohmic or not.

8 Rose and Rachel are trying to find the resistance of an electrical device. They find that, at 5.0 V, it draws a current of 200.0 mA and at 10.0 V it draws a current of 500.0 mA. Rose says that the resistance is 25.0 Ω, but Rachel maintains that it is 20.0 Ω. Judge who is correct and provide reasons for your choice.

9 An experiment is conducted to gather data about the relationship between current and potential difference for three ohmic devices, labelled A, B and C. The data is used to plot an *I*–*V* graph for each device, as shown in the graph.



a For a given potential difference, sequence the devices in order of highest current to lowest current drawn.

b Sequence the devices in order of highest resistance to lowest resistance.

10 The table below shows measurements for the potential difference and corresponding current for an ohmic conductor.

***V* (V)**	0	2	3	V_2
***I* (A)**	0	0.25	I_1	0.60

Determine I_1 and V_2.

11 A student conducted an experiment to determine the resistance of three ohmic conductors. They used a variable power source and measured the current across the conductors for different applied voltages. The table shows the data they collected.

Conductor 1		Conductor 2		Conductor 3	
***V* (V)**	***I* (A)**	***V* (V)**	***I* (A)**	***V* (V)**	***I* (A)**
1	0.01	1	0.003	1	0.05
2	0.02	2	0.006	2	0.10
3	0.03	3	0.009	3	0.15

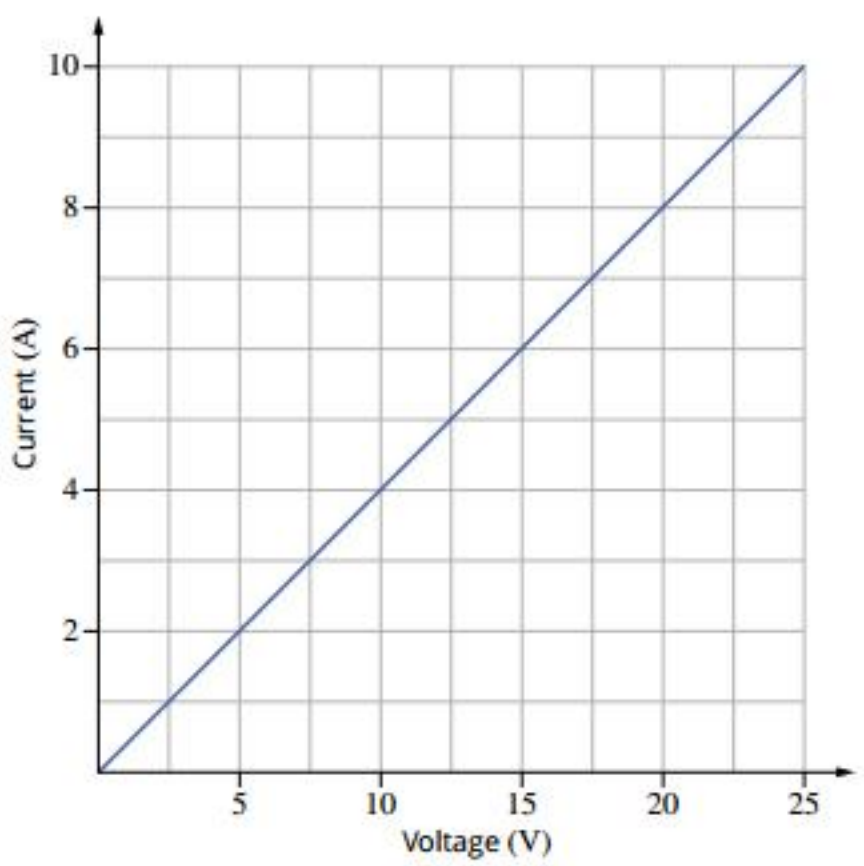
a Identify the independent and dependent variable in the experiment.

b Draw *I*–*V* graphs for each conductor on the same set of axes.

c Comment on and compare the resistance of each conductor based on the shape of the graph.

d Calculate the resistance of each conductor.

12 A student obtains a graph of the current–voltage characteristics of a piece of resistance wire, as shown.

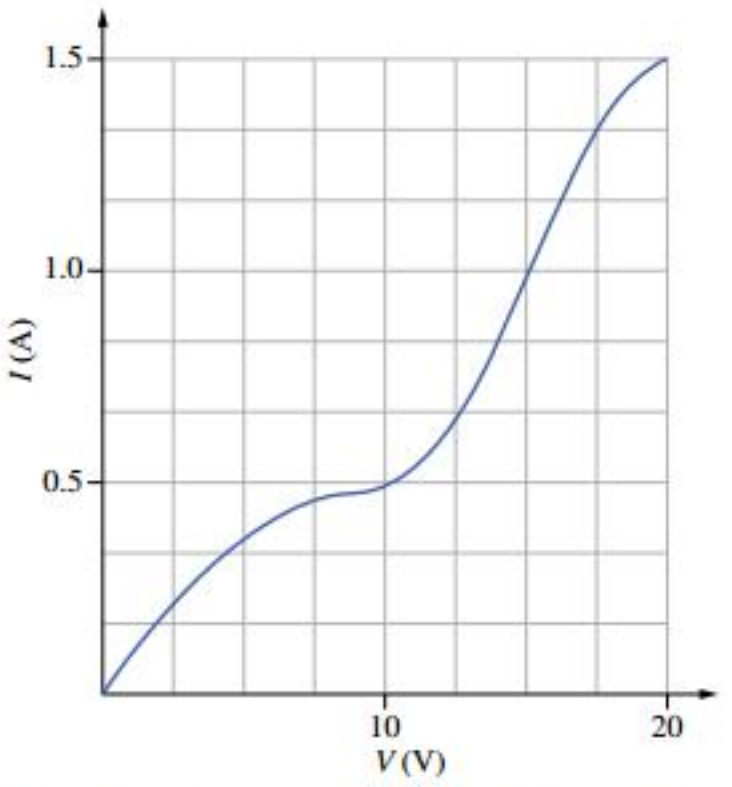


a Explain whether this piece of wire is ohmic or non-ohmic.

b Determine the current that flows in this wire at a voltage of 7.5V.

c Calculate the resistance of this wire.

13 A strange electrical device has the *I*–*V* characteristics shown on the graph.



a Identify whether the device is ohmic or non-ohmic and explain your answer.

b Determine the current that is drawn when a voltage of 10V is applied to the device.

c Calculate the voltage that is required to double the current drawn at 10V.

d Determine the resistance of the device for each of the following voltages.

i 10V

ii 20V

4.6 Power

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe power dissipation over resistors in a circuit
- recall the formula $P = \frac{W}{t}$
- solve problems involving power.

If you wanted to buy a new phone charger, you might wonder how you could determine how quickly the charger will charge up the battery on your phone. Printed on all appliances is a rating for the **power** of that device. Power is the rate at which energy is transferred or transformed by the components within the device.

POWER

Whenever energy is being transferred from one place to another, or transformed from one form to another, 'work' is being done. (Work is covered in more detail in Chapter 8.) Power, P, can be described as the rate at which work, W, is done over t seconds.

$$P = \frac{\text{energy transferred}}{\text{time}} = \frac{W}{t}$$

The unit for work is the watt, where 1 watt (W) = 1 joule per second (J s^{-1}).

The more powerful an appliance is, the faster it can do a given amount of work. In other words, an appliance that draws more power can do the same amount of work in a shorter amount of time. If you want something done quickly, then you need an appliance that has a higher power rating.

Power is the rate at which energy is transferred or transformed – in other words, the rate at which work is done.

$P = \frac{W}{t}$

where

P is power in watts (W)

W is energy transferred in joules (J)

t is time in seconds (s)

1 watt (W) = 1 joule per second (J s^{-1}).

Worked example 4.6.1

USING $P = \frac{W}{t}$

An appliance has a power rating of 2.0 kW and is run for 30 minutes. Calculate the work done.

Thinking	Working
Identify the relationship needed to solve the problem.	$P = \frac{W}{t}$
Convert to SI units.	$P = 2\,\text{kW} = 2000\,\text{W}$ $t = 30\,\text{minutes} = 30 \times 60 = 1800\,\text{s}$
Identify the required values from the question, substitute and calculate the work done.	$P = \frac{W}{t}$ $W = Pt$ $= 2000 \times 1800$ $= 3.6 \times 10^6\,\text{J}$

➤ Try yourself 4.6.1

USING $P = \frac{W}{t}$

An appliance has a power rating of 100 W and is run for 15 minutes. Calculate the work done.

POWER DISSIPATION

When designing electrical circuits, it is important to consider not only the components required to perform a specific task but also their ability to survive under normal operating conditions. Resistors are often used in circuits to dissipate electrical power by causing a voltage drop across them. This is done by transforming electrical potential energy into unwanted energy, usually in the form of heat energy. Most resistors have a marked power rating to ensure that the user knows the maximum amount of power that can be dissipated by the resistor without burning it out. The power dissipated across resistors is discussed in more detail in Chapter 5.

4.6 Review

SUMMARY

- Power is the rate at which energy is transferred or transformed in a circuit component. It is defined and quantified by the relationship:

$$P = \frac{W}{t}$$

- Power dissipation occurs when energy is transformed through components in a circuit into unwanted forms of energy such as heat.

KEY QUESTIONS

Describe

1 Describe 'power'.

2 Give an equation for power, P, in terms of energy transformed, W, and time, t.

3 State what has happened to a resistor that has burned out.

Apply

4 Explain how energy-efficient light bulbs can produce the same amount of light and do the same amount of work as incandescent light bulbs if they have a much lower power rating.

Analyse

5 Determine the power in the energy transformation for a smartphone charged with 3J of energy in one second.

6 A freezer has a power rating of 460W. It is designed to be connected to 230V.

Calculate the work performed by the freezer in 5.0 minutes.

7 A lightbulb that is connected to 240V uses 3.6kJ of electrical potential energy in exactly one minute. Calculate the power of the lightbulb.

8 A hair dryer has a power rating of 800.0W. It is operational when connected to a mains supply of 240V. Calculate how much energy is transferred when the hair dryer is used for 2.0 minutes.

9 A resistor has a maximum power rating of 20W. It transforms 35J of electrical potential energy into 35J of heat energy. Calculate the amount of time the resistor can run before damage is done to it by burning it out.

Chapter review

04

KEY TERMS

ammeter
amperes
atom
charge
conductor
conventional current
coulomb
current
drift velocity
electrical circuit
electrical potential energy
electricity
electron flow
elementary charge
insulators
ion
ionised
law of conservation of charge
metal
net charge
non-metal
non-ohmic
ohmic
potential difference
power
resistance
resistor
transfer
transform
voltmeter
volts

KEY QUESTIONS

Describe

1 Identify which of the following charged particles are moving when an electric current flows in a circuit:
- **A** negatively charged electrons
- **B** positively charged electrons
- **C** positively charged protons
- **D** both negative and positive charges

2 An electron, q_1, is attracted to a second charge, q_2. Determine the signs of each charge.
- **A** q_1 = positive, q_2 = positive
- **B** q_1 = negative, q_2 = negative
- **C** q_1 = positive, q_2 = negative
- **D** q_1 = negative, q_2 = positive

3 State the term used to describe the energy available to electric charges moving in a circuit.

4 Identify the constant of proportionality in Ohm's law.
- **A** voltage
- **B** current
- **C** resistance
- **D** electrical potential

5 Determine the power in the energy transformation for a device charged with 2 J of energy in one minute.
- **A** 0.03 W
- **B** 0.5 W
- **C** 2 W
- **D** 30 W

Apply

6 Select the option which best describes the law of conservation of charge.
- **A** The net charge of an object remains unchanged.
- **B** The net charge of a system remains constant.
- **C** If a charge is destroyed, a new charge is created.
- **D** When two charges are brought close together, they will combine.

7 Determine the electrical potential energy stored in a car battery that provides 4000 C of charge at 16 V.
- **A** 4×10^{-3} J
- **B** 250 J
- **C** 6.4×10^{4} J
- **D** 4000 J

8 Explain why separating charges within a battery produces an electrical potential difference.

9 Select the option that best explains why water flowing in a pipe is a common analogy for electric current.
- **A** Water does not conduct electricity.
- **B** Water can leak out of a pipe.
- **C** Water is not compressed or lost as it flows through a pipe.
- **D** Water and electricity do not mix.

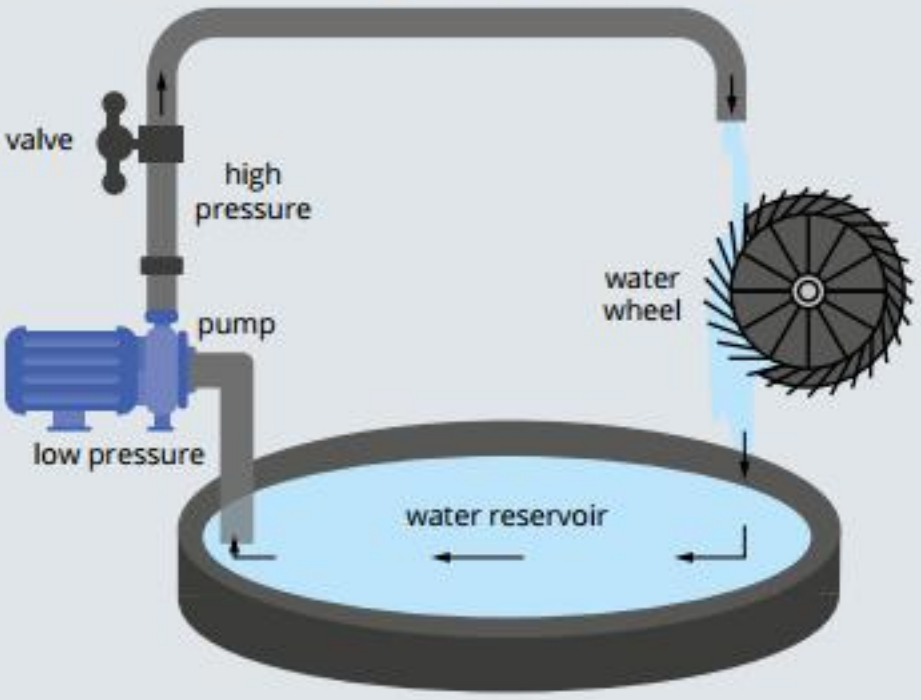
10 Identify which of the following best describes what the bicycle-chain analogy shows.
- **A** Electrons physically touch one another.
- **B** Only a small number of electrons move.
- **C** Electrons are the same shape as the links in a bicycle chain.
- **D** Electrons move simultaneously in every part of the circuit.

11 Explain why even a good conductor such as copper wire provides some resistance to current.

Analyse

12 Contrast current and potential difference.

13 Consider the following analogy of an electric circuit.



Describe the energy at different points in the water circuit and explain how this relates to the energy inputs and outputs of an electric circuit.

14 Determine the gradient of an *I–V* graph for an ohmic conductor with a resistance of 25Ω in a circuit connected to a 12V power supply.

A gradient = 0.04
B gradient = 0.48
C gradient = 0.5
D gradient = 2.1

15 An alpha particle consists of two protons and two neutrons. Calculate the charge on an alpha particle.

16 A current of 1.6A flows for 100.0seconds. Calculate:

a the amount of charge, in coulombs, that moves past a point in this time
b the number of electrons that move past a point in this time.

17 A battery does 2.0J of work on a charge of 0.50C to move it from point A to point B. Calculate the potential difference between the two points A and B.

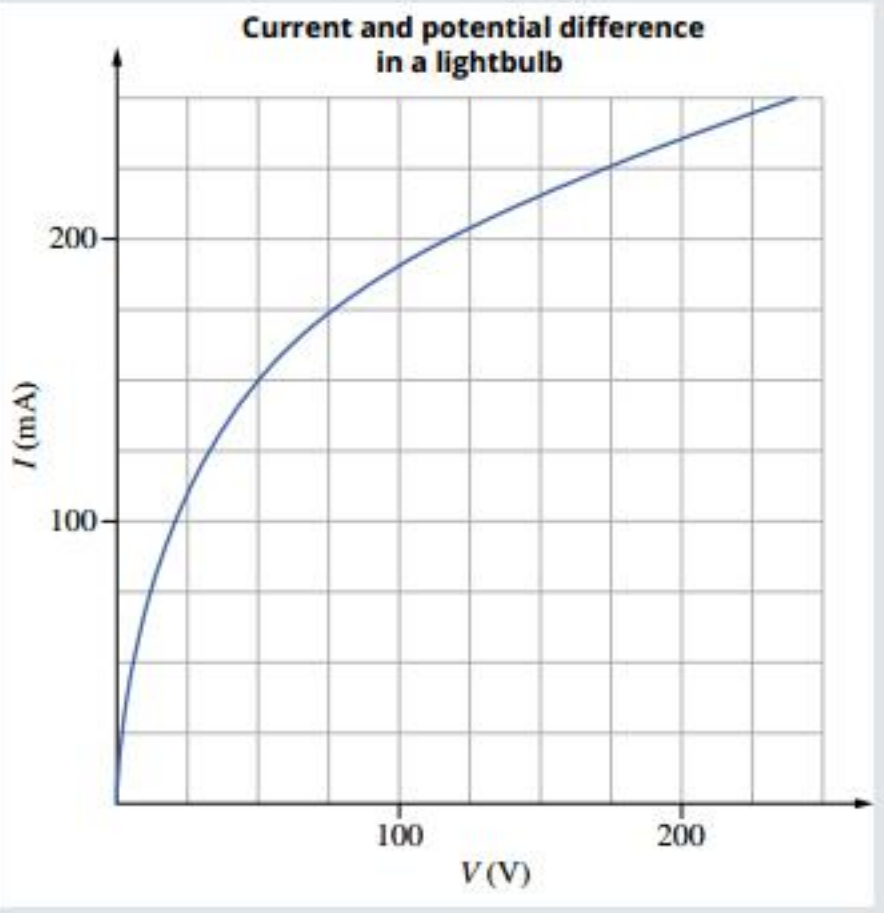
18 Calculate how much power an appliance uses if it does 2500J of work in 30.0minutes.

19 A battery gives a single electron 1.4×10^{-18}J of energy. Calculate the potential difference supplied by the battery.

20 A student finds that the current through a wire is 5.0A when a voltage of 2.5V is applied to it. Calculate the resistance of the wire.

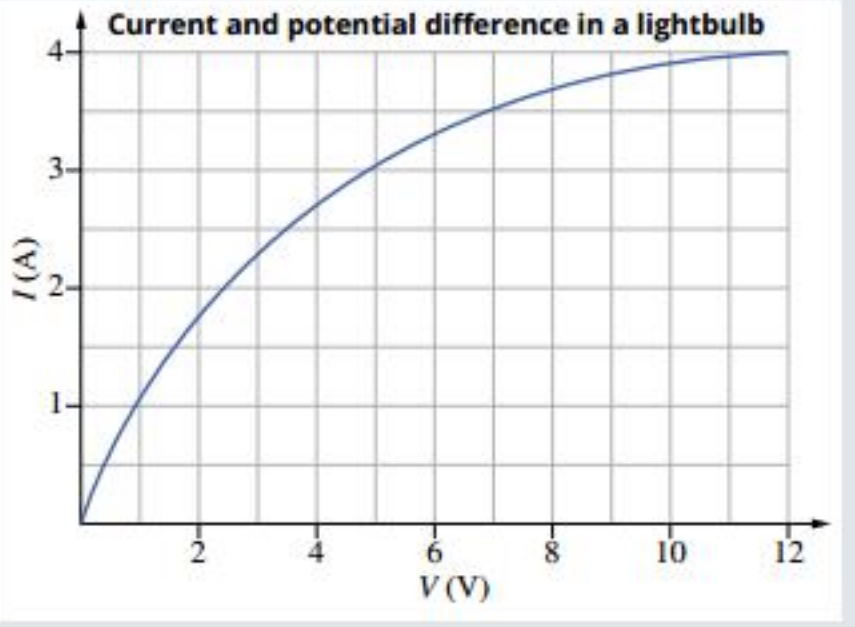
21 A 60.0W incandescent globe draws 0.25A when connected to a 240V power supply. Calculate the resistance of the globe.

22 Calculate the resistance at 50.0V of the non-ohmic conductor in the *I–V* graph shown.

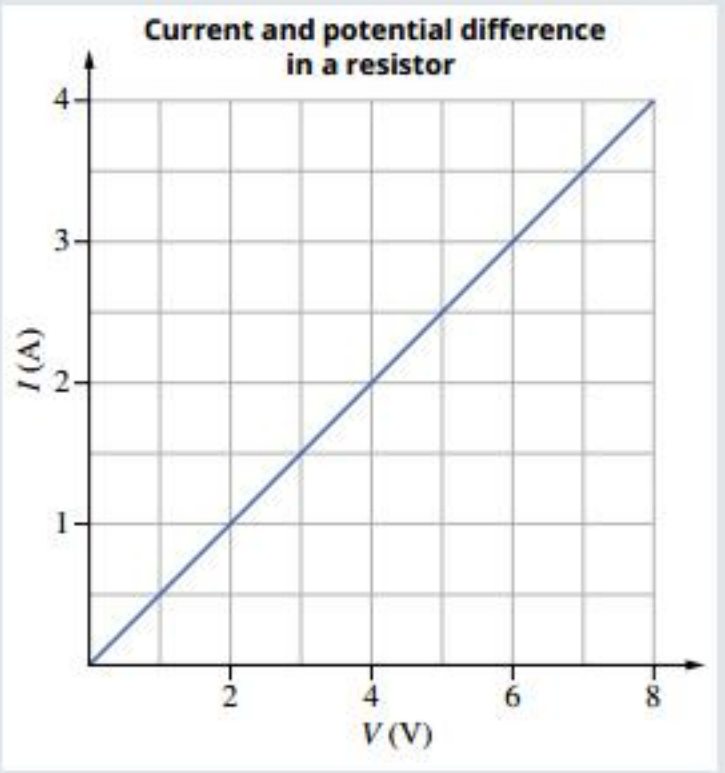


23 The *I–V* graph of a non-ohmic conductor is shown below. Calculate the resistance of the conductor for each of the following voltages.

a 1.0V
b 7.0V
c 12.0V



24 Siobhan is measuring the current flowing through an ohmic conductor as she varies the potential difference of the power source. The results are shown in the graph shown. Calculate the resistance when the potential difference is 1.0 V.



25 A 120 V lamp draws 12.5 A when cold but only 0.800 A when hot. Calculate the resistance of the lamp at each temperature.

26 If 0.80 A of current flows through a lightbulb, calculate the number of electrons that enter the lightbulb each second.

27 A 3.0 V torch with a 0.30 A bulb is switched on for 1 minute.

a Calculate how much charge has travelled through the filament in this time.

b During this time 54 J of energy were used. Deduce where this energy has come from.

Interpret

28 A circuit contains a 50.0 Ω resistor and a power supply. The circuit is connected for 10.0 s, and during this time a charge of 5.00 C flows past a point in a circuit. Determine:

a the current in the circuit

b the potential difference across the resistor

c how much energy the resistor dissipates during this time.

29 A simple circuit contains a 100.0 Ω resistor and a 10.0 V power supply. Determine the number of electrons that flow through a point in the circuit if the circuit is connected for 1.0 minute.

Data analysis

DATA SET 1

The information below applies to Questions 1–4.

An experiment was conducted to investigate the relationship between voltage and current.

The research question was:

What is the relationship between voltage and current in an ohmic resistor?

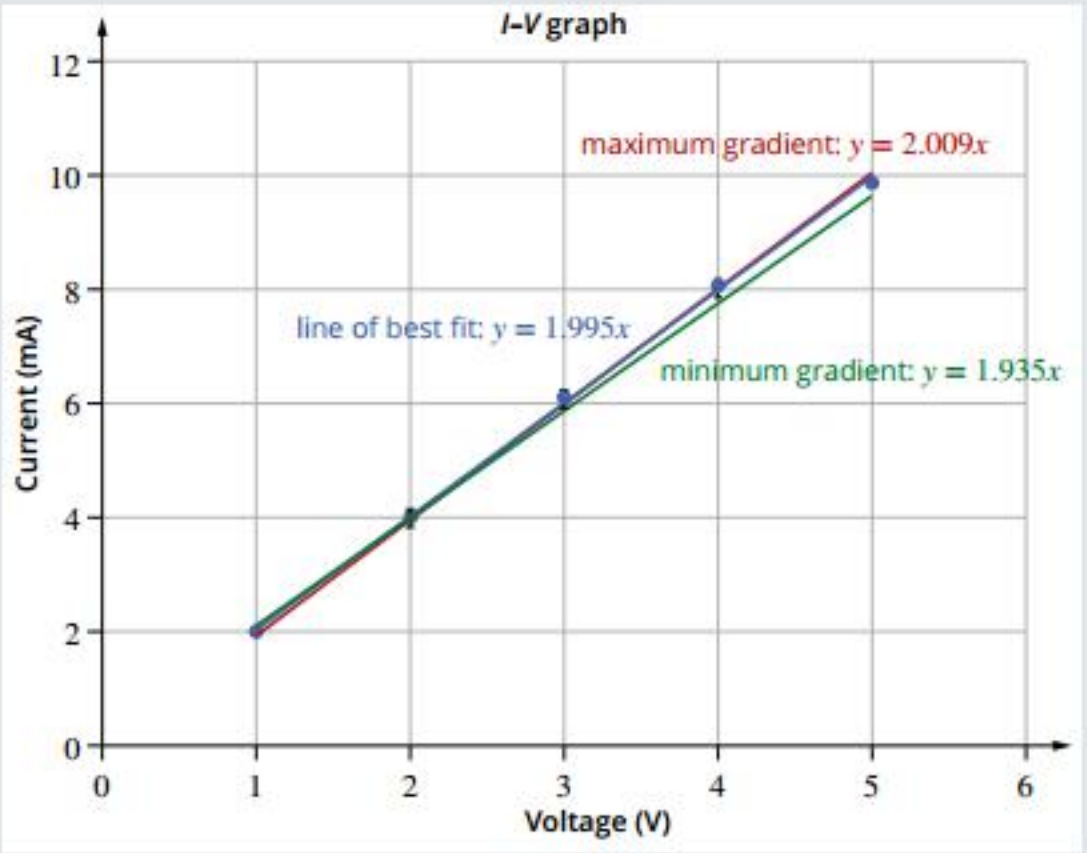
A variable power source was connected in series to an ohmic resistor.

The circuit also included a voltmeter and ammeter to measure the voltage of the circuit and the current across the resistor.

The resistor's colour-band showed it was a 500Ω resistor with a 5% tolerance.

The amount of energy supplied to the circuit was changed in the variable power source in increments of 1V, from 0V to 5V, and the current through the resistor was measured.

Voltage (V)	Current (mA)
1	2.1
2	3.9
3	6.0
4	8.1
5	9.9



Question 1 (1 mark)

Calculate the uncertainty in the gradient using the equation:

$$\text{Uncertainty} = \frac{\text{maximum gradient} - \text{minimum gradient}}{2}$$

Question 2 (1 mark)

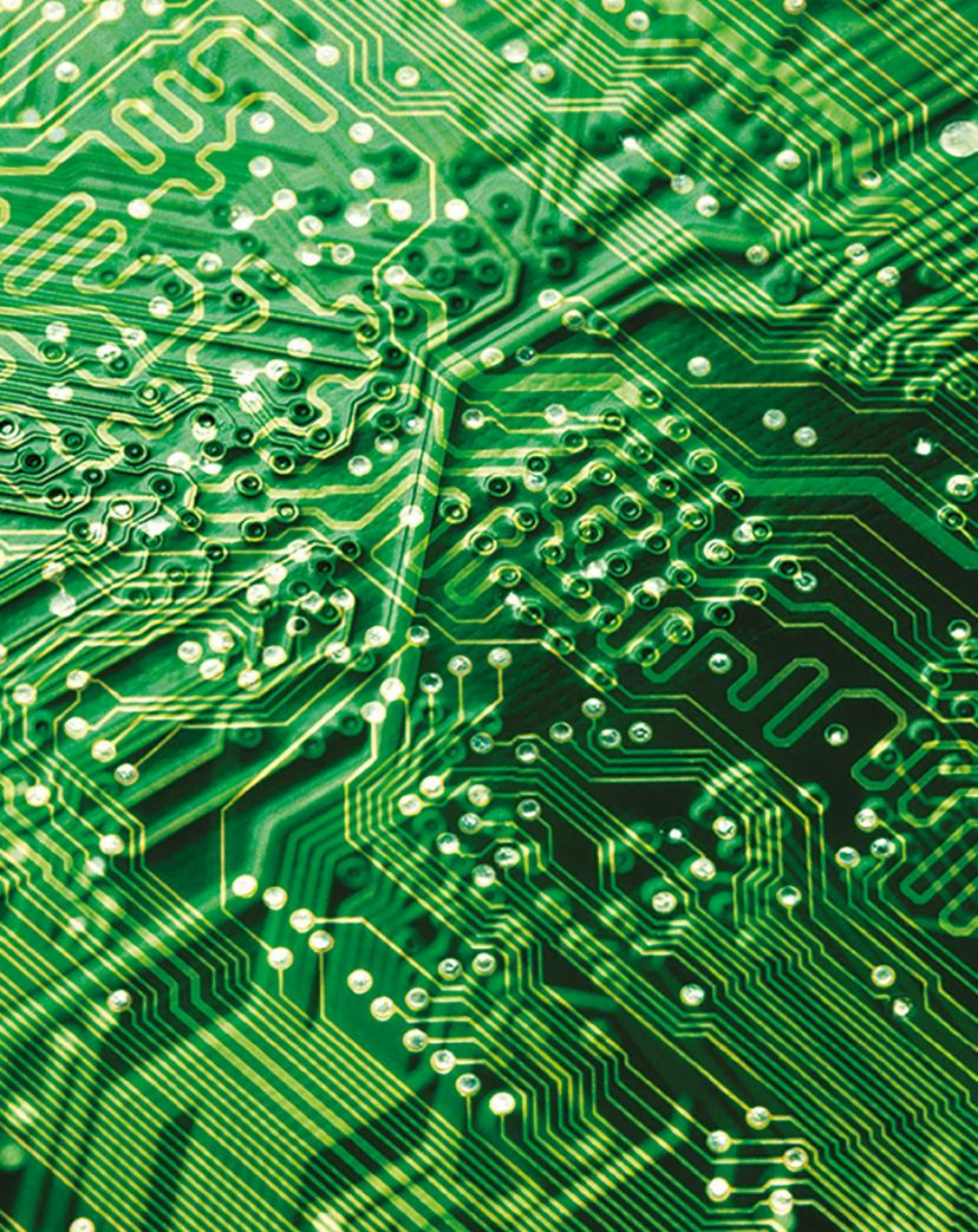
Identify the relationship between voltage and current.

Question 3 (4 marks)

Draw a conclusion that quantifies the resistance of the resistor, including the percentage uncertainty in your result. Show your reasoning.

Question 4 (1 mark)

Use the data set to draw a conclusion about the accuracy of the claimed tolerance of the resistor.



CHAPTER

05 Electrical circuits

Electrical circuits are the basis of much of our modern society. This chapter introduces a range of circuits, from simple series circuits to the complex parallel wiring systems found in a modern home. Electrical circuits can be used to perform energy transfers and transformations through devices such as lightbulbs, thermistors, light-dependent resistors and light-emitting diodes. It is essential that anyone working with electricity learns how to do so safely in the home and laboratory. Understanding key concepts related to electric circuits, including voltage, current, resistance and power, in both series and parallel circuits, allows you to implement the required safety mechanisms when dealing with electricity.

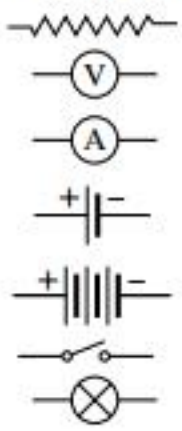
Syllabus subject matter

CURRENT, POTENTIAL DIFFERENCE AND ENERGY FLOW

- Explain that electric charge is conserved at all points in an electrical circuit. **5.4**
- Explain that the energy inputs in a circuit equal the sum of energy output from loads in the circuit. **5.4**
- Describe the concepts of electrical potential difference and power within a circuit. **5.2, 5.3, 5.4**

CIRCUIT ANALYSIS AND DESIGN

- Describe simple series, parallel and series/parallel circuits. **5.1, 5.2, 5.3, 5.4**
- Describe the concept of power dissipation over resistors in a circuit. **5.2, 5.3, 5.4**
- Construct electrical circuit diagrams using the following symbols, **5.1, 5.2, 5.3, 5.4**



- Solve problems involving electrical potential difference, electric current, resistance and power. **5.2, 5.3, 5.4**
- Describe series and parallel connections of components in electrical circuits. **5.2, 5.3, 5.4**
- Solve problems involving finding equivalent resistance, electrical potential difference and electric currents in series and parallel circuits using $P = V_t$, $P = I^2R$, $V_t = V_1 + V_2 + \ldots V_n$, $R_t = R_1 + R_2 + \ldots R_n$, $I_t = I_1 + I_2 + \ldots I_n$, $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$ **5.2, 5.3, 5.4**
- Describe simple series, parallel and series/parallel circuits. **5.1, 5.2, 5.3, 5.4**

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5.1 Electrical circuits

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand simple electrical circuits and read circuit diagrams
- measure current and voltage using an ammeter, voltmeter or multimeter.

SIMPLE ELECTRICAL CIRCUITS

As you will recall from Chapter 4, a flow of electric charge is called an electric current. Current can be carried by moving electrons in a wire or by ions in solution. This section explores current as it flows through wires in **electrical circuits**. Recall from Chapter 4 that an electrical circuit is a path made of conductive material, through which charges flow (an electric current) in a closed loop. Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.

Electrical circuits are involved in much of the technology used every day. To construct electrical circuits, you must know about the components of a circuit and be able to read circuit diagrams (Figure 5.1.1).

FIGURE 5.1.1 Circuit diagrams, simple or complex, are used to help us to construct electrical circuits.

Common symbols for electronic components

Several different components can be added to a circuit. It is not necessary to be able to draw detailed pictures of these components; simple symbols are much clearer. The common symbols used to represent the electrical components in electrical circuits are shown in Figure 5.1.2a.

Circuit diagrams

When constructing a building, it is important that the builder has a clear set of instructions from the designer. This is as much the case for an electrical circuit as it is for a tall building or a motor vehicle.

Circuit diagrams are used to clearly show how the components of an electrical circuit are connected. They simplify the physical layout of the circuit into a diagram that is recognisable by anyone who knows how to interpret it. You can use the list of common symbols for electrical components to interpret circuit diagrams (Figure 5.1.2a).

The circuit diagram in Figure 5.1.2b shows how a cell (or battery), resistor, switch and lightbulb are connected in a circuit. The circuit can be traced by following the straight lines representing the connecting wires.

a

Device	Symbol
wires crossed not joined	
wires joined, junction of conductor	
fixed resistor	
lightbulb	
earth or ground	

Device	Symbol
cell (DC supply)	
battery of cells (DC supply)	
ammeter	
voltmeter	
switch open	
switch closed	

b

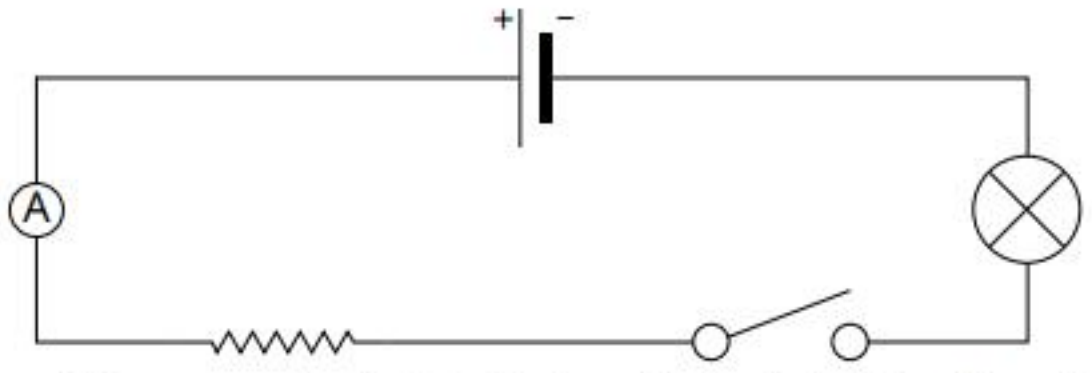


FIGURE 5.1.2 (a) Some commonly used electrical devices and their symbols, which can be used in circuit diagrams, and (b) a simple circuit diagram.

Conventional current vs electron flow

On a circuit diagram, current is indicated by a small arrow and the symbol *I*. This shows the conventional current or just current. Recall from Chapter 4 that the direction of conventional current is opposite to the direction of electron flow, as it was originally thought that the charges that flowed in circuits were positive and flowed from the positive terminal to the negative terminal. This convention is still used today, even though scientists know now that it is the negative charges (electrons) that flow around a circuit.

FIGURE 5.1.3 A digital ammeter (labelled with an A) measures current in a circuit (in this case 0.15 A).

MEASURING CIRCUITS

In this section, you will learn how to measure the current and voltage in a circuit using simple meters, and how to correctly connect them.

Measuring current: the ammeter

A device called an ammeter measures current. The ammeter (Figure 5.1.3) is connected along the same path taken by the current flowing through the lightbulb (Figure 5.1.4). This is referred to as connecting the ammeter 'in series'. The circuit is connected in series so there is only one path for the current to take. The positive terminal of the ammeter is connected so that it is closest to the positive terminal of the power supply. The negative terminal of the ammeter is closest to the negative terminal of the power supply.

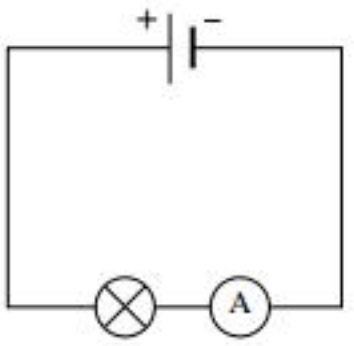


FIGURE 5.1.4 A circuit diagram showing an electric cell, a lightbulb and an ammeter connected in series

Measuring the current is possible because charge is conserved at all points in a circuit. This means that the current is the same at all points in a series circuit. The current that flows into a lightbulb is the same as the current that flows out of the lightbulb. An ammeter can, therefore, be connected before or after the lightbulb in series to measure the current. The concept of conservation of charge will be explored further in Module 5.2.

Table 5.1.1 lists some typical values for electric current in various situations.

TABLE 5.1.1 Typical values for electric current

Situation	Current
1 electron moving past a point per second	10^{-19} A
nerve fibres in body	1 μA
pocket calculator	5 mA
mobile phone charger	200 mA (input), 1.5 A (output)
lightbulb	400 mA
USB port	500–900 mA
laptop charger	1.4 A (input), 2.3 A (output)
toaster	3 A
hair dryer	9 A
fan heater	10 A
starter motor in car	200 A
lightning	10000 A
current flowing between Jupiter and its closest moon, Io, caused by charged particles escaping Io's volcanoes moving in Jupiter's huge magnetic field	3×10^6 A

Measuring voltage: the voltmeter

Recall from Chapter 4 that the voltage, or potential difference, is what gives electrons the energy to travel around a circuit. Voltage is a measure of the amount of energy per unit charge that a charge has. A device called a 'voltmeter' measures voltage.

Voltmeters are wired into circuits differently from ammeters. Unlike an ammeter, which measures the current passing through a wire, a voltmeter measures the change in voltage (potential difference) as current passes through a particular component. This means that one wire of the voltmeter is connected to the circuit before the component and the other wire is connected to the circuit after the component; that is, as an extra side loop to the main circuit (Figure 5.1.5). This is called connecting the voltmeter 'in parallel'. Parallel circuits will be investigated in more depth in Module 5.3.

In Figure 5.1.6, the voltmeter is connected to the circuit on either side of the lightbulb, that is, in parallel. This is so that it can measure the voltage drop (potential difference) across the lightbulb. Like the ammeter, it is important to connect the voltmeter with the positive terminal closest to the positive terminal of the power supply. The voltmeter's negative terminal is connected closest to the negative terminal of the power supply.

FIGURE 5.1.6 A voltmeter measures the voltage change (in this case, 6.23 V) across a lightbulb. Note that the voltmeter is connected to either side of the lightbulb as an extra small loop attached to the main circuit (in parallel).

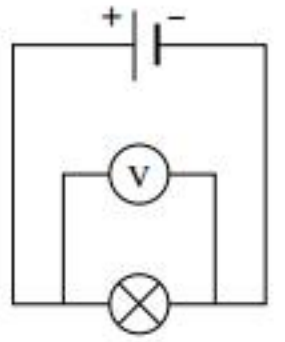


FIGURE 5.1.5 A circuit diagram showing an electric cell, with a lightbulb and a voltmeter connected in parallel

An ammeter measures current, *I*, in amps (A) and is connected in a circuit in series.

A voltmeter measures the potential difference or voltage, *V*, in volts (V) and is connected in a circuit in parallel.

Multimeters

The internal circuitry of a voltmeter is significantly different from that of an ammeter. Electricians and scientists who work with electrical circuits often find it inconvenient to keep collections of voltmeters and ammeters, so they have found a way to bundle the circuitry for both meters up into a single device known as a **multimeter** (Figure 5.1.7).

This is much more convenient because the multimeter can be quickly switched from being an ammeter to being a voltmeter as needed. However, when a multimeter is switched from one mode to another, it is important to make a corresponding change to the way it is connected to the circuit being measured. An ammeter is connected in series and a voltmeter in parallel. In fact, if a multimeter is working as an ammeter and it is connected in parallel like a voltmeter, it may draw so much current that its internal circuitry will be burnt out and the multimeter will be destroyed.

FIGURE 5.1.7 A digital multimeter can be used as either an ammeter or a voltmeter.

Internal resistance

Resistors and lightbulbs are not the only components in a circuit to have a resistance. Recall from Chapter 4 that everything a charge moves through in a circuit resists the flow of the charge. Cells and batteries also have their own **internal resistance** that affects the output voltage and the current through the circuit. For the copper wire connecting other elements of a circuit, this internal resistance is negligible (extremely low) and you can ignore it for calculations.

Ideally, the meters you use to measure current or voltage in a component of a circuit do not disturb the circuit in which they are connected. An ideal ammeter has zero resistance so it can measure the current that flows through it without affecting the current that flows in the circuit. An ideal voltmeter has an infinitely large resistance so that, when it is connected in parallel, it does not offer an alternative pathway for the charges in the circuit. Batteries, cells and meters will not interfere with the circuit they measure, so you do not need to consider their internal resistance in your calculations.

Short circuits

If a path is created in a circuit with little to no resistance, the electrons will flow through that path rather than the circuit. For example, if an ammeter (which has negligible internal resistance) is connected in parallel to a component, the electrons will prefer to flow along that arm of the circuit. This is known as a short circuit (Figure 5.1.8).

A short circuit can be dangerous in electrical circuits because the current flowing along the path will be very large (as the resistance is very small and $V = IR$). Potentially, this can cause the circuit component that the current is moving through – the ammeter in Figure 5.1.8 – to overheat.

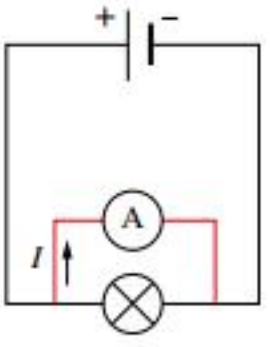


FIGURE 5.1.8 A short circuit allows the current to flow along an unintended path that has little or no resistance.

5.1 Review

SUMMARY

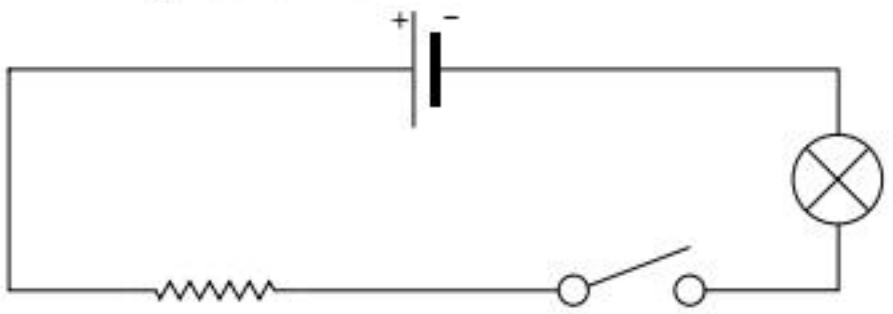
- Simplified diagrams can be used to represent electrical circuits.
- Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.
- Conventional current in a circuit flows from the positive terminal to the negative terminal.
- Current is measured with an ammeter connected along the same path as the current flowing within the circuit (in series).
- Voltage, or potential difference, is measured with a voltmeter connected to either side of the component (in parallel) in the circuit.
- A multimeter can be used to measure either current or voltage, depending on how it is connected in a circuit.

KEY QUESTIONS

Describe

1 List the requirements for current to flow in a circuit.

2 List the electronic devices shown in the circuit diagram, starting from the top of the diagram and moving anticlockwise.



3 Name the component you would use to measure the following in a circuit, and state how you would connect it to the circuit.

a the current

b the voltage

4 Name the units used for measuring voltage and current.

Apply

5 Explain why scientists refer to conventional current as flowing from positive to negative.

6 Draw a circuit diagram for a circuit containing the following items set up correctly.

a a cell, a lightbulb and an ammeter

b a cell, a lightbulb and a voltmeter

7 Explain why an ammeter is set up in series, whereas a voltmeter is set up in parallel.

8 Explain why an open switch in a series circuit will cause the electric current to stop flowing.

Analyse

9 **a** Construct a circuit diagram that contains a battery and two lightbulbs set up:

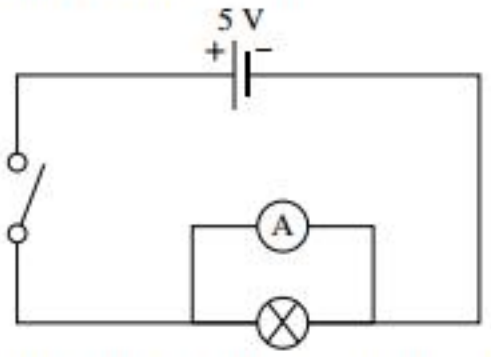
i in series

ii in parallel.

b Add a single switch to each of your circuits from part **a** so that both lights will turn off if the switch is open.

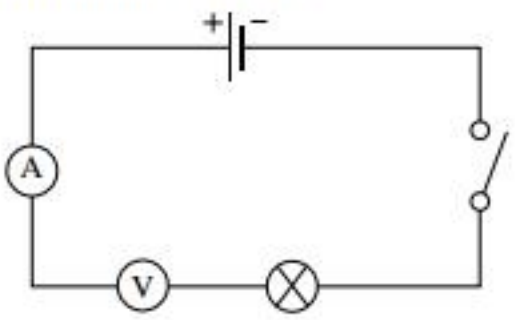
10 **a** A student wants to measure the current flowing in a circuit. They set up an ammeter as shown in the diagram below. When they turn the power supply on, the ammeter reading is extremely high and it stops working.

Deduce what this tells you about the internal resistance of the ammeter and the path that the current took in this circuit.



b The student then set up an ammeter in series and added a voltmeter as shown in diagram below. They noticed that the ammeter reading was almost zero and the lightbulb was not lit

Recalling Ohm's law, $V = IR$, from Chapter 4, consider what you can deduce about the internal resistance of the voltmeter.



5.2 Series circuits

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand what a series circuit is
- describe simple series circuits
- calculate the equivalent series resistance for a number of resistors in series
- determine the voltage, resistance and/or current in a circuit with a group of resistors connected in series
- apply Ohm's law to the equivalent series resistance to calculate the current drawn by a group of resistors connected in series.
- describe power dissipation over resistors in a series circuit
- calculate power in series circuits using $P = VI$ and $P = I^2R$

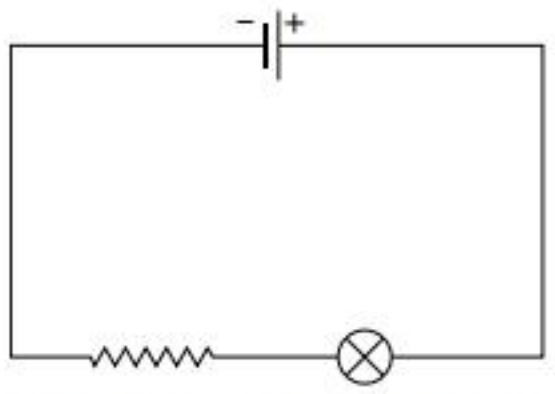


FIGURE 5.2.1 This circuit has a resistor and lightbulb connected in series, so there is only one path for the current to flow.

Some circuits contain more than one electrical component. In a **series circuit**, components are connected one after another in a continuous loop, and there is only one way for the current to flow. Components connected in this way are said to have been connected 'in series'. The circuit shown in Figure 5.2.1 shows a resistor and a lightbulb connected in series with an electric cell.

Series circuits are very easy to construct, but they have some disadvantages. As every component is connected one after the other, the components are dependent on each other. If one component is removed or breaks down, the circuit is no longer a closed loop and no current will flow. Figure 5.2.2 shows how removing a lightbulb from a series circuit interrupts the entire circuit. Due to this characteristic, series circuits with more than one component are not commonly used in the home.

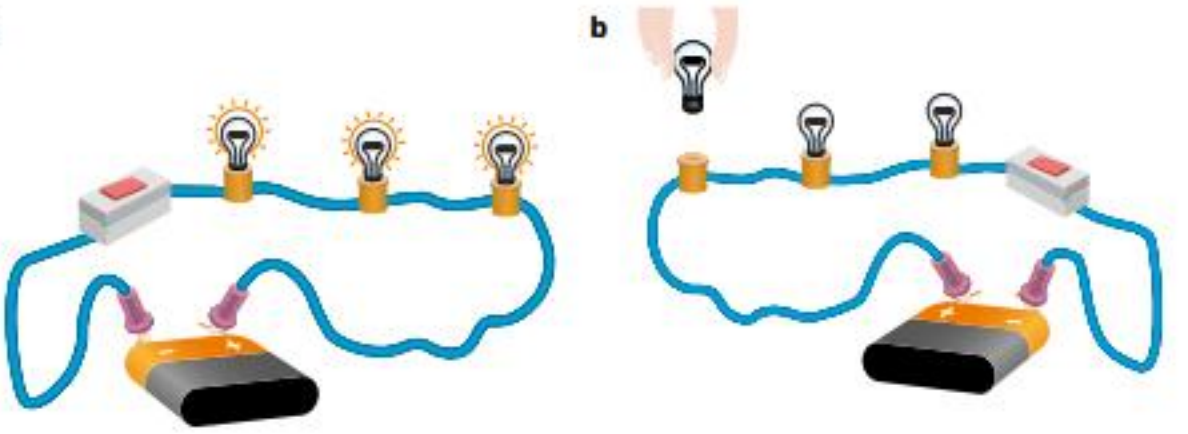


FIGURE 5.2.2 (a) All components in the circuit are intact and so the circuit is a closed loop. (b) When one lightbulb is removed, the whole circuit is interrupted so no current flows and no lightbulbs light up.

CONSERVATION OF CHARGE

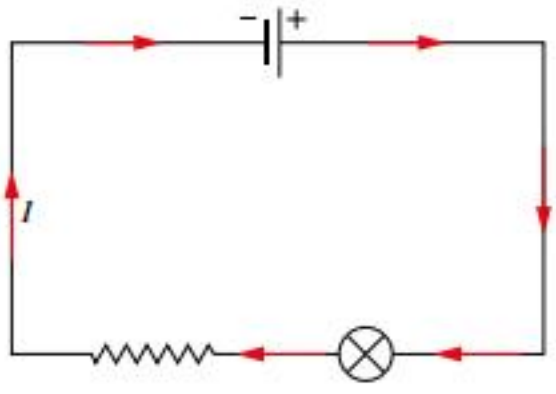


FIGURE 5.2.3 In a series circuit, the same current flows through each component.

When analysing a series circuit, it is important to understand that the same amount of current flows in every part of the circuit. Electric charges are not created or destroyed within an electrical circuit, so the current flowing out of the cell must be the same as the current flowing through the lightbulb, which is also the same as the current flowing through the resistor. This current also flows unchanged back into the cell (Figure 5.2.3). The unchanging nature of the amount of charge flowing in and out of a component in a circuit is known as the **law of conservation of electric charge**.

The current in a series circuit is the same in every part of the circuit.

The current (that is, the number of electrons) entering a component in a circuit must be equal to the current (the number of electrons) leaving the component.

EQUIVALENT SERIES RESISTANCE

Consider the circuit in Figure 5.2.4. When analysing this circuit, it might be tempting to apply $V = IR$ to each resistor using the potential difference supplied by the cell for V. However, the potential difference is split between R_1 and R_2, so the potential difference across resistor R_1 is not the same as the potential difference supplied by the cell. Similarly, the potential difference across lightbulb R_2 is not the same as the potential difference supplied by the cell. If $V_{supply} = IR_1$ was used to calculate the current flowing in the circuit, the answer would be incorrect.

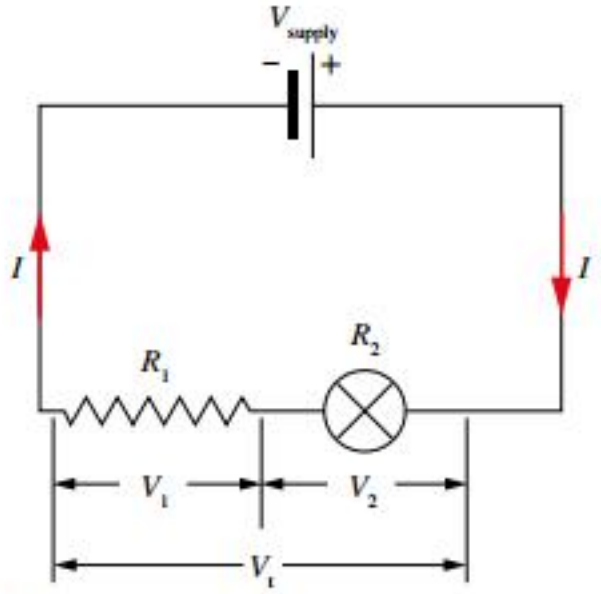


FIGURE 5.2.4 Using Ohm's law, it is possible to show the relationship between the potential difference supplied by the cell, V_{supply}, the current flowing in the circuit, I, and the resistances of the two components R_1 and R_2.

To calculate voltage supplied by the cell, the voltage drop across each resistor should be considered. The law of conservation of energy tells you that the energy supplied by the cell must be the same as the energy transformed by the components in the circuit (for example, the resistor and the lightbulb), so no energy can be lost or created. Therefore, the potential difference across the cell (the voltage gain) must be equal to the total potential difference across the circuit (the voltage drop):

$$V_{supply} = V_t = V_1 + V_2$$

If the resistance of the fixed resistor is R_1, the resistance of the lightbulb is R_2 and the current flowing through both R_1 and R_2 is I, then applying Ohm's law, $V = IR$, to the voltage drop over each resistor gives:

$$V_t = I \times R_1 \text{ and } V_2 = I \times R_2$$

The total voltage drop, V_t, across the two components is the sum of the individual voltage drops:

$$V_t = V_1 + V_2 = IR_1 + IR_2 = I \times (R_1 + R_2)$$

This equation shows the relationship between the potential difference supplied by the cell and the potential differences of the lightbulb and resistor. The last part of the equation also shows that the total resistance of the lightbulb and resistor in series is the sum of their individual resistances. The lightbulb and resistor could be replaced with a single resistor, without changing the current in the circuit, if the single resistor has a resistance equal to $R_1 + R_2$.

In general, for any circuit:

$V_t = V_1 + V_2 + \ldots + V_n$

where

V_t is the voltage supplied by the cell, or the total voltage

$V_1, V_2, \ldots, V_n$ are the individual voltage drops.

Figure 5.2.5 shows that two resistors can be replaced with a single resistor. In general, an **equivalent resistance** can replace several individual resistors connected in series. This is equal to the sum of the individual resistances and is also called the equivalent series resistance or total resistance, R_t.

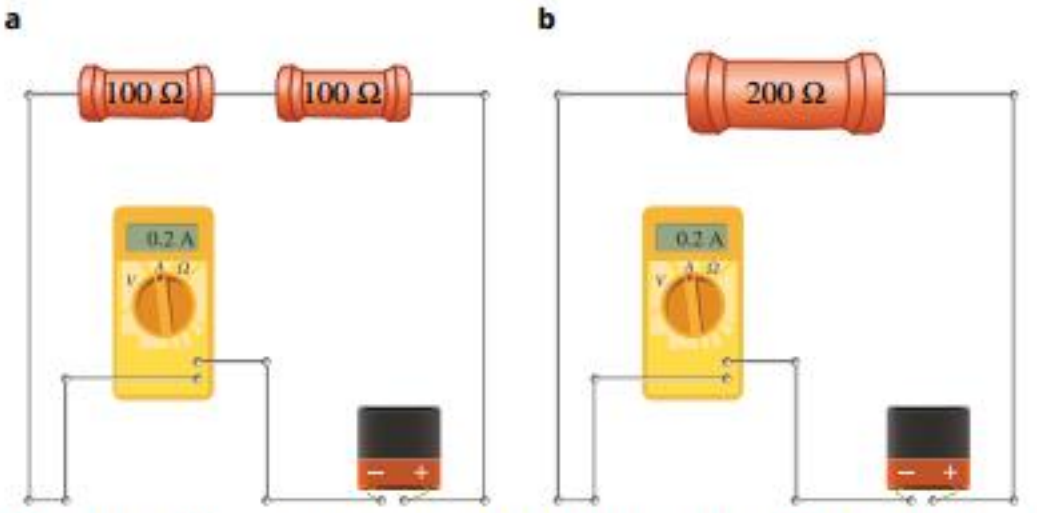


FIGURE 5.2.5 (a) Two 100 Ω resistors can be replaced with (b) a single 200 Ω resistor to draw the same current in a circuit.

Equivalent resistances can be used in circuit analysis to simplify a complicated circuit diagram so that current and potential difference can be determined.

Identical resistors in series

Where identical resistors are placed in series, the total resistance of the combination can be found by simply multiplying the value of one of the resistors by the number of resistors.

For example, three 4 Ω resistors connected in series would have an equivalent resistance of 12 Ω.

$$R_t = 4\,\Omega \times 3 = 12\,\Omega$$

The three 4 Ω resistors in series could be replaced with a single 12 Ω resistor.

$R_t = R_1 + R_2 + \ldots + R_n$
where
R_t is the equivalent series resistance, or total resistance
$R_1, R_2, \ldots, R_n$ are the individual resistances.

Worked example 5.2.1

CALCULATING AN EQUIVALENT SERIES RESISTANCE

A 100.0 Ω resistor is connected in series with a 690 Ω resistor and a 1.20 kΩ resistor. Calculate the equivalent series resistance.

Thinking	Working
Recall the formula for equivalent series resistance.	$R_t = R_1 + R_2 + \ldots + R_n$
Substitute in the given values for resistance. Make sure to convert kΩ to Ω. Solve to find the equivalent series resistance.	$R_t = 100.0 + 690 + 1200$ $= 1990\,\Omega$

➤ Try yourself 5.2.1

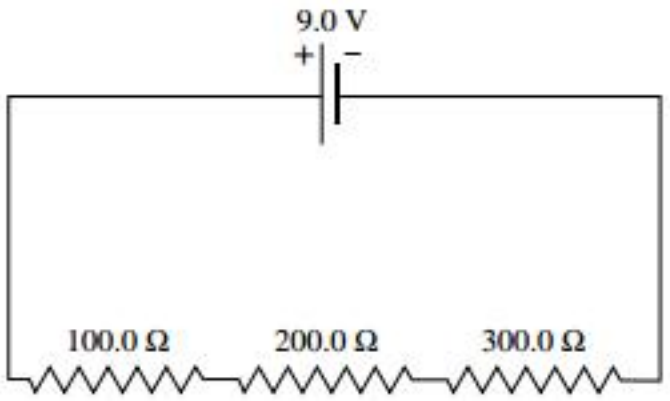
CALCULATING AN EQUIVALENT SERIES RESISTANCE

A string of Christmas lights consists of 20 lightbulbs connected in series. Each lightbulb has a resistance of 8.0 Ω. Calculate the equivalent series resistance of the Christmas lights.

Worked example 5.2.2

USING EQUIVALENT SERIES RESISTANCE FOR CIRCUIT ANALYSIS

Use an equivalent series resistance to calculate the current flowing in the series circuit below and the potential difference across each resistor. Comment on the sum of the potential differences.

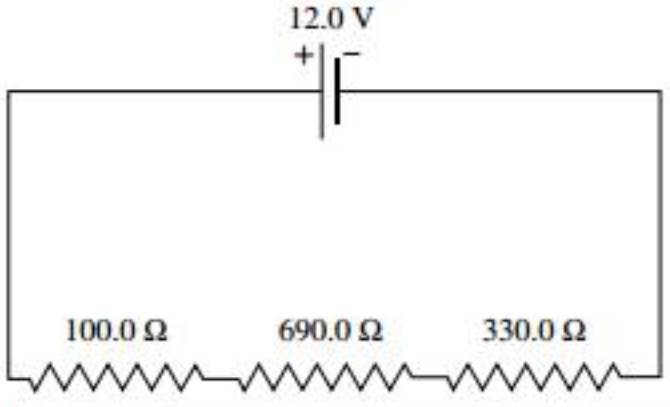


Thinking	Working
Recall the formula for equivalent series resistance.	$R_t = R_1 + R_2 + R_3 + \ldots + R_n$
Find the equivalent (total) resistance in the circuit.	$R_t = 100.0 + 200.0 + 300.0$ $= 600.0\,\Omega$
Rearrange Ohm's law, $V = IR$, to make I the subject and calculate the current in the circuit. Whenever calculating current in a series circuit, use R_t and the voltage of the power supply.	$I = \frac{V}{R}$ $= \frac{9.0}{600.0}$ $= 0.015\,A$ $= 15\,mA$
Use Ohm's law, $V = IR$, to calculate the potential difference across each separate resistor.	$V = IR$ $V_1 = 0.015\,A \times 100.0\,\Omega$ $= 1.5\,V$ $V_2 = 0.015\,A \times 200.0\,\Omega$ $= 3.0\,V$ $V_3 = 0.015\,A \times 300.0\,\Omega$ $= 4.5\,V$
Add up the individual potential differences.	$V_t = 1.5 + 3.0 + 4.5 = 9.0\,V$ This is the same as the supply voltage.

➤ Try yourself 5.2.2

USING EQUIVALENT SERIES RESISTANCE FOR CIRCUIT ANALYSIS

Calculate the current flowing in the series circuit below and the potential difference across each resistor, using an equivalent series resistance. Comment on the sum of the individual potential differences.



POWER DISSIPATION

The law of conservation of energy states that energy cannot be created or destroyed. This means that, in every energy transformation, all the energy inputs are equal to the energy outputs. When energy is transferred out of a system, it can be described as 'wasted' energy. For example, when you use a computer, you might notice it warm up over time. This is because, as the computer transforms electrical energy into light energy to display the screen (useful energy); it also transforms electrical energy into heat energy that is not useful to the system. It is transferred to the surrounding environment; it is 'wasted'.

Some components in a circuit, such as resistors and lightbulbs, transform energy into heat and/or light. Power is transferred away (dissipated) into the surroundings across these components.

Recall from Chapter 4 that the power used by a circuit is the rate at which energy is transformed by the circuit:

$$P = \frac{W}{t}$$

where P is the power (W), W is the energy transformed (J) and t is the time (s).

The power used across a circuit or dissipated by individual components can also be calculated using potential difference, current and resistance.

Potential difference, V, is defined as the amount of electrical potential energy, W, given to each coulomb of charge, q:

$$V = \frac{W}{q}$$

In electrical circuits, electrical potential energy is transformed into other forms of energy. Work is done when energy is transformed from one form to another. (Work is covered in more detail in Chapter 8.) The amount of electrical potential energy transformed in the circuit is equal to the work done by the circuit, so that W is also equal to the work done by a circuit.

Rearranging the definition of voltage, therefore, gives a formula for work, W:

$$W = Vq$$

Using the definition of current:

$$I = \frac{q}{t}$$

$$q = It$$

Therefore:

$$W = VIt$$

Finally, combine this with the power equation above:

$$P = \frac{W}{t} = \frac{VIt}{t} = VI$$

$P = VI$

where

P is power (W)

V is potential difference (V)

I is current (A).

A second equation for power can be derived by combining the equation for power, $P = VI$, with Ohm's law, $V = IR$.

$$P = VI$$
$$P = (IR) \times I$$
$$P = I^2R$$

$P = I^2R$

where

P is power (W)

I is current (A)

R is the resistance (Ω).

Power dissipation in series circuits

The power dissipated across components can be calculated if you know two of the following values:

- the current through the component
- the potential difference across the component
- the resistance of the component.

You can use either version of the power equation (either $P = VI$ or $P = I^2R$) for this calculation.

These equations can also be used to calculate the power dissipated across an entire series circuit by:

- calculating the equivalent series resistance using $R_t = R_1 + R_2 + \ldots + R_n$
- calculating the current in the circuit using Ohm's law (if it is not known)
- substituting the values into either power equation.

Make sure that you input the correct variables depending on what you are calculating. For example, if you are calculating the power dissipated across an individual resistor, make sure you use the resistance or voltage drop of that specific resistor and not the voltage from the battery, cell or equivalent resistance of the circuit.

Maximum power rating of resistors

Resistors come in different shapes and sizes. They resist the flow of current and, in doing so, they transform electrical energy into heat energy. Depending on the size and substance of the resistor, there is a maximum amount of electrical energy that they can transform into heat energy before they are damaged. This is the resistor's 'maximum power rating'. Generally, the larger the surface area of the resistor (the bigger the resistor), the larger the power rating (Figure 5.2.6).

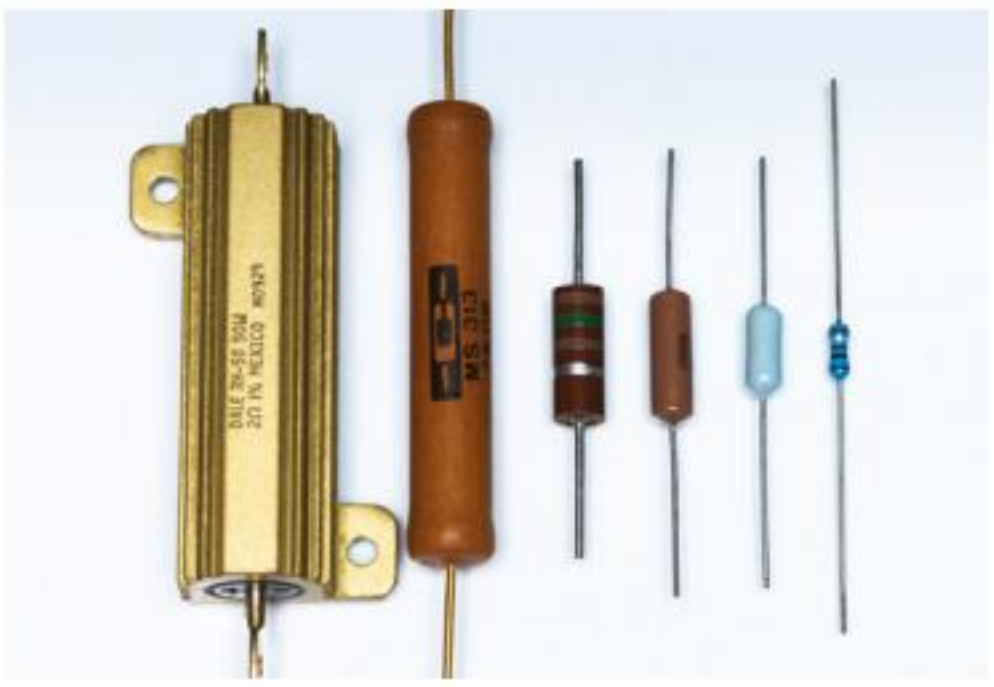
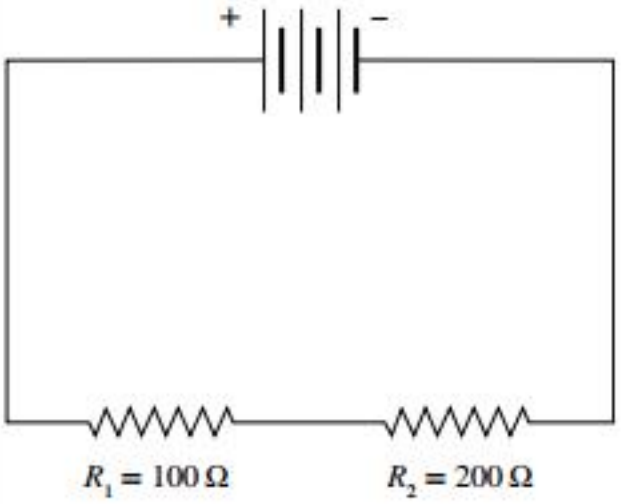


FIGURE 5.2.6 In general, the larger the resistor, the greater its power rating. For example, the smallest resistor (less than 1 cm long) shown here has a much lower power rating than the longest resistor, on the left, with a power rating of 50 W.

Worked example 5.2.3

CALCULATING POWER IN SERIES CIRCUITS

Two resistors, R_1 and R_2, are connected in series to a battery supplying 12 V.



a Calculate the power in the circuit.

Thinking	Working
Recall the formula for equivalent series resistance.	$R_t = R_1 + R_2 + R_n$
Find the equivalent (total) resistance in the circuit.	$R_t = R_1 + R_2$ $= 100 + 200$ $= 300\,\Omega$
Rearrange Ohm's law, $V = IR$, to make I the subject. Use this equation to calculate the current in the circuit. Whenever calculating current in a series circuit, use R_t and the voltage of the power supply.	$I = \frac{V}{R}$ $= \frac{12}{300}$ $= 0.04\,\text{A}$
Recall the formula for power.	$P = VI$
Use the power equation to calculate the power supplied to the series circuit.	$P = VI$ $= 12 \times 0.04$ $= 0.48\,\text{W}$

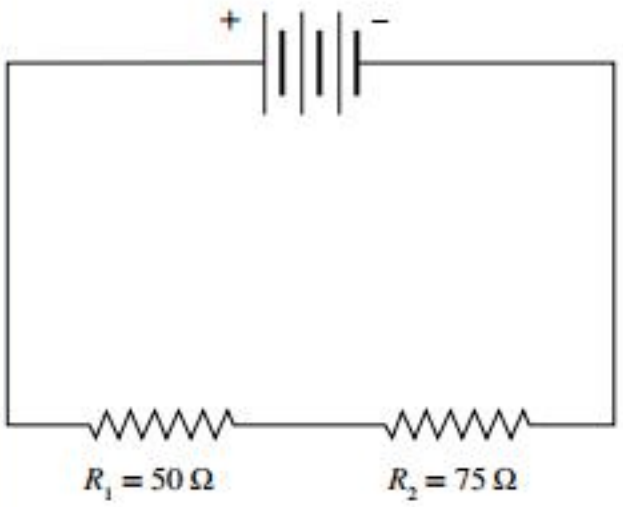
b Calculate the power dissipated across each resistor.

Thinking	Working
Use the power equation ($P = I^2R$) to calculate the power dissipated across each resistor. Note that you could use $P = VI$ to determine the power dissipated by each resistor, but you would then need to calculate the potential difference across each resistor by first applying Ohm's law.	$P_1 = I^2R$ $= 0.04^2 \times 100$ $= 0.16\,\text{W}$ $P_2 = I^2R$ $= 0.04^2 \times 200$ $= 0.32\,\text{W}$

➤ Try yourself 5.2.3

CALCULATING POWER IN SERIES CIRCUITS

Two resistors, R_1 and R_2, are connected in series to a battery supplying 20 V.



a Calculate the power in the circuit.

b Calculate the power dissipated across each resistor.

Note that in Worked Example 5.2.3 the sum of the power dissipated across each resistor is equal to the total power of the series circuit. This is because energy is conserved in all transformations. Hence, the total power (P_t) is given by:

$$P_t = P_1 + P_2 + \ldots + P_n$$

5.2 Review

SUMMARY

- When resistors are connected in series, the:
  - current through each resistor is the same
  - sum of the potential differences is equal to the potential difference (voltage) supplied to the circuit:

$$V_{supply} = V_t = V_1 + V_2 + \ldots + V_n$$

  - equivalent resistance R_t is equal to the sum of the individual resistances:

$$R_t = R_1 + R_2 + R_3 + \ldots + R_n$$

  - Ohm's law, $V = IR$, can be applied to calculate the current drawn by a group of resistors connected in series:

$$I = \frac{V_t}{R_t}$$

- Ohm's law can also be applied to individual components in a series circuit.
- Power supplied to a series circuit or dissipated by a component can be calculated using either of the following equations:
  - $P = VI$, where P is the power, V is the potential difference, and I is the current.
  - $P = I^2R$, where P is the power, I is the current, and R is the resistance
- Power can be dissipated across components in a circuit when energy is transformed.
- Resistors have a maximum power rating that is related to their size. This power rating determines the maximum amount of current that can pass through the element without overheating it.

5.2 Review *continued*

KEY QUESTIONS

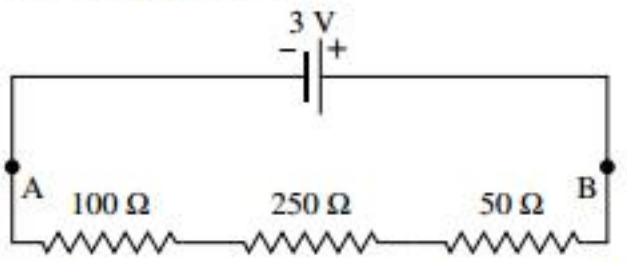
Describe

1 Write an equation for the equivalent resistance in a series circuit.

2 Define power dissipation.

Apply

3 Consider the circuit shown. Explain whether the current at point A would be greater than, less than or the same as at point B.

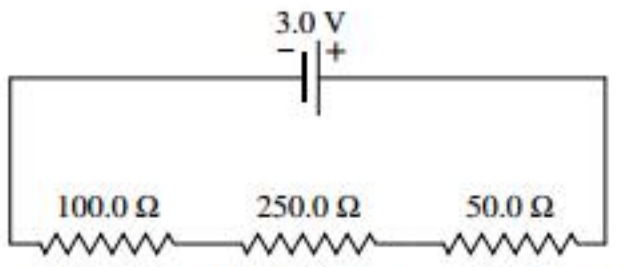


4 Two 20.0Ω resistors are connected in series with a 6.0V battery. Determine the voltage drop across each resistor.

5 An incandescent lightbulb is connected to a series circuit. Describe how power is dissipated across this component.

Analyse

6 Consider the series circuit shown.



a Calculate the equivalent resistance of the group of three resistors.

b Calculate the current flowing in the circuit.

c Calculate the potential difference across the 100.0Ω resistor in the circuit.

7 Two resistors, R_1 and R_2, are connected in series to a battery supplying 15V:

$R_1 = 10\Omega$

$R_2 = 5\Omega$

a Calculate the power of the series circuit.

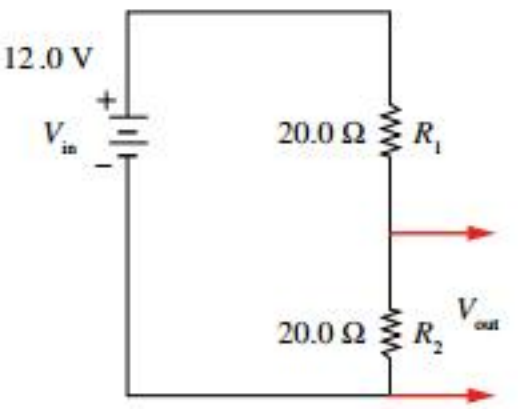
b Calculate the power dissipated across each resistor.

8 Two 100.0Ω resistors and a 200.0Ω resistor are connected in series with an 8.0V battery.

a Calculate the current flowing in the circuit.

b Calculate the voltage drop across one of the 100.0Ω resistors.

9 A voltage divider circuit, like the one shown in the diagram below, is simply a series circuit with two or more components. The circuit is called a voltage divider because the voltage supplied to the circuit is shared (or divided) between the components in the circuit. This voltage divider circuit has a 12.0V battery and two 20.0Ω resistors.



a Calculate the total resistance of the circuit.

b Calculate the current flowing through the circuit.

c Calculate V_{out}, the potential difference across R_2.

10 Two resistors are connected in series to a cell that is supplying 15V:

$R_1 = 30\Omega$

$R_2 = 45\Omega$

a Calculate the power dissipated across each resistor using both of the following equations:

$P = I^2R$

$P = VI$

b One of the resistors has a maximum power rating of 1.5W. Determine which resistor this applies to for the circuit to be safely operated in its current set-up.

5.3 Parallel circuits

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand what a parallel circuit is
- describe simple parallel circuits
- determine the voltage, resistance and/or current in a circuit with a group of resistors connected in parallel
- calculate the equivalent parallel resistance for a number of resistors in parallel
- apply Ohm's law to the equivalent parallel resistance to calculate the current drawn by a group of resistors connected in parallel.
- describe power dissipation over resistors in a parallel circuit
- calculate the power in parallel circuits using $P = VI$ and $P = I^2R$.

One of the disadvantages of series circuits is that if a switch is opened or a device is disconnected, then the circuit is broken and current stops flowing. In everyday life, you often want to switch devices on and off independently. **Parallel circuits** allow you to do this.

The circuit diagram in Figure 5.3.1 shows a simple parallel circuit. Even if switch A is open (as shown), lightbulb B will still light up as it is part of an unbroken complete circuit that includes the battery. Similarly, if switch A is closed and switch B is open, current will light up lightbulb A and not lightbulb B. Alternatively, both switches could be closed to light up both lightbulbs or both switches could be opened to switch both lamps lightbulbs.

In a series circuit, all the components are in the same loop and, therefore, the same current flows through each component. In contrast, each loop of a parallel circuit acts like an independent circuit with its own current. Where the current divides, and also where it rejoins, is called a junction.

Consider again the water analogy used in Chapter 4. When water flows through pipes, it is not lost. If the pipe splits in two, some of the water flows in one pipe, and the remaining water will flow in the other pipe. If the two sections rejoin, the water comes back together again flowing at the same rate, just as it was before the pipe was split. The same occurs with charges flowing in a parallel circuit.

Figure 5.3.2 shows that each individual charge goes through one lightbulb or the other. This means that although the current in the main part of the circuit remains constant, and the readings on ammeters A_1 and A_2 will be the same, the current through each lightbulb will be different, because in the parallel section the current is divided between the two branches.

FIGURE 5.3.1 In this parallel circuit, lightbulb A will be off and lightbulb B will be on.

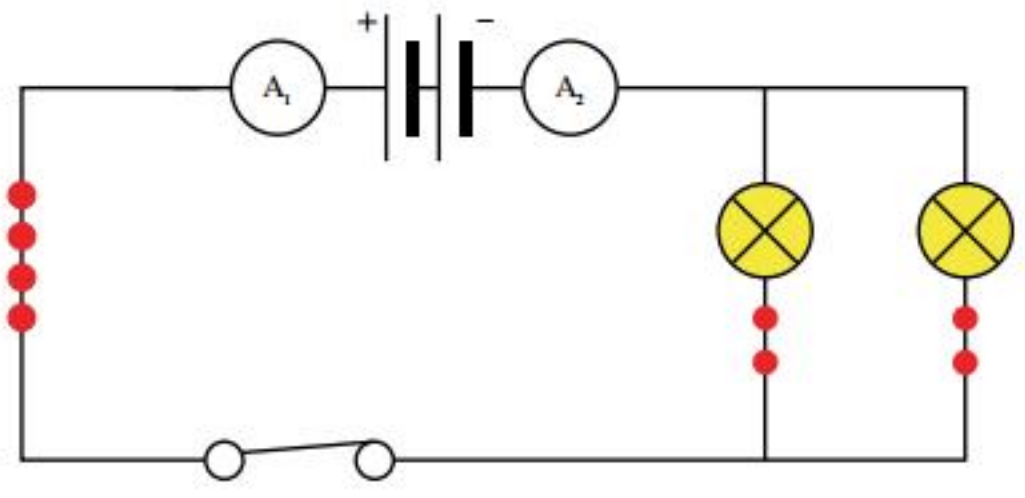


FIGURE 5.3.2 Unlike a series circuit, charges flowing in a parallel circuit have a choice of path. Here there are two paths for current to flow (indicated by two red dots) and two junctions where the circuit branches and then rejoins the main circuit (indicated by four red dots).

The current in the main part of a parallel circuit is the sum of the currents in each branch of the circuit as the charges recombine to give the total current.

$$I_t = I_1 + I_2 + \ldots + I_n$$

The voltage drop is the same over each branch of a parallel circuit.

If the lightbulbs are identical, as in the circuit in Figure 5.3.2, the current will be split evenly between the two lightbulbs:

$$I_1 = I_2 = \frac{I_t}{2}$$

In a parallel circuit the voltage is not shared between resistors, unlike a series circuit. The voltage is the same across each branch of a parallel circuit. This is because, although the charges take different pathways, they have the same amount of energy per charge no matter which path they take. In the water analogy, a pump (the battery) can be used to raise the water to a certain level above the ground. The water will have gravitational potential energy, which will cause it to flow back down through the pipe to the ground, where it will flow back to the pump. If another pipe is added next to the original one, some water will flow down each pipe, but the potential energy due to gravity of the water at the top of each pipe will be the same, and the difference in potential energy of the water between the top of the pipe and the bottom of the pipe (where it is zero) will be the same for the two pipes.

An advantage of parallel circuits is that lightbulbs connected in this way are brighter than if they were connected in series, because the potential energy of the charges is not shared between the lightbulbs.

EQUIVALENT PARALLEL RESISTANCE

When additional resistors are added in a series circuit, the total resistance of the circuit increases. Additional resistance means that less current flows through the circuit.

In contrast, adding an additional resistor in parallel means that more current flows through the circuit because another path for charges has been added. This means that the total resistance for the circuit decreases.

Parallel circuits are more complicated than series circuits, so the formula used to calculate the equivalent (total) resistance is more complicated. The total current in a parallel circuit is given by $I_t = I_1 + I_2$, where I_1 and I_2 are the individual currents that flow in two parallel branches of the circuit. Substituting this into Ohm's law gives you an equation for calculating the resistance in parallel circuits:

$$I = \frac{V}{R}$$

$$I_t = I_1 + I_2$$

$$\frac{V}{R_t} = \frac{V}{R_1} + \frac{V}{R_2}$$

The voltage drop across each branch of a parallel circuit is the same, so cancel V:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$$

For a general parallel circuit with n resistors:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

where

R_t is the equivalent resistance

$R_1, R_2, \ldots R_n$ are the individual resistances.

Worked example 5.3.1

CALCULATING AN EQUIVALENT PARALLEL RESISTANCE

A 100Ω resistor is connected in parallel with a 300Ω resistor. Calculate the equivalent parallel resistance.

Thinking	Working
Recall the formula for equivalent resistance.	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
Substitute in the given values for resistance. Solve for R_t.	$\frac{1}{R_t} = \frac{1}{100} + \frac{1}{300}$ $= \frac{3}{300} + \frac{1}{300}$ $= \frac{4}{300}$ $R_t = \frac{300}{4}$ $= 75\ \Omega$

➤ Try yourself 5.3.1

CALCULATING AN EQUIVALENT PARALLEL RESISTANCE

A 20.0Ω resistor is connected in parallel with a 50.0Ω resistor. Calculate the equivalent parallel resistance.

The equivalent resistance of a set of resistors connected in parallel will always be smaller than the smallest resistor in the set.

In a parallel circuit:

$$R_t < R_{\text{smallest resistor}}$$

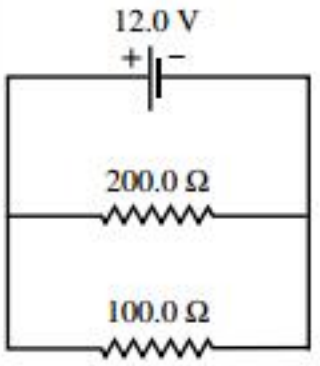
Notice that in the previous worked example, the equivalent resistance was smaller than the smallest individual resistance. This is because adding a resistor provides an additional pathway for current. More current flows, so the resistance of the circuit has been effectively reduced.

Consider the resistors in Try yourself 5.3.1. The smaller individual resistor is 20.0Ω. The addition of the 50.0Ω resistor in parallel allows the current an extra pathway and therefore it is easier for the current to flow through the combination. The equivalent resistance of the pair must be less than the 20.0Ω alone.

Worked example 5.3.2

USING EQUIVALENT PARALLEL RESISTANCE FOR CIRCUIT ANALYSIS

Two resistors are connected in parallel to a 12.0V cell, as shown below.



a Determine the equivalent parallel resistance, R_t.

Thinking	Working
Recall the formula for equivalent parallel resistance.	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
Substitute in the given values for resistance.	$\frac{1}{R_t} = \frac{1}{100.0} + \frac{1}{200.0}$
Solve for R_t.	$\frac{1}{R_t} = \frac{2}{200.0} + \frac{1}{200.0} = \frac{3}{200.0}$ $R_t = \frac{200.0}{3} = 66.67\,\Omega$

b Determine the current flowing through each resistor.

Thinking	Working
Use Ohm's law to calculate the current through each separate resistor. Remember that the voltage through each branch is the same as the voltage of the power supply, which is 12.0V.	100.0Ω resistor: $I_{100} = \frac{V}{R} = \frac{12.0}{100.0} = 0.120\,\text{A}$ 200.0Ω resistor: $I_{200} = \frac{V}{R} = \frac{12.0}{200.0} = 0.0600\,\text{A}$

c Determine the total current flowing through the circuit.

Thinking	Working
The total current is the sum of the currents through each branch.	$I_t = I_{100} + I_{200}$ $= 0.120 + 0.060$ $= 0.180\,\text{A}$

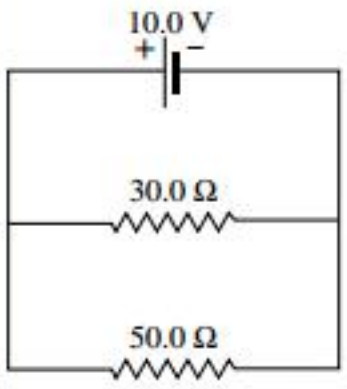
d Compare the sum of the individual currents to the total current.

Use Ohm's law to calculate the current in the circuit. To calculate I, use the voltage of the power supply and the total resistance.	$I_{circuit} = \frac{V}{R} = \frac{12.0}{66.67} = 0.180\,\text{A}$
Compare the sums of total current and individual currents.	$I_{circuit} = 0.180\,\text{A}$ $I_t = 0.180\,\text{A}$ The sum of the individual currents is equal to the total current.

➤ Try yourself 5.3.2

USING EQUIVALENT PARALLEL RESISTANCE FOR CIRCUIT ANALYSIS

A current flows through each resistor of the parallel circuit shown below.



a Determine the equivalent parallel resistance, R_t.

b Determine the current flowing through each resistor.

c Determine the total current flowing through the circuit.

Identical resistors in parallel

When identical resistors are placed in parallel, the equivalent resistance of the combination can be found by simply dividing the value of one of the resistors by the number of resistors.

For example, three 12 Ω resistors connected in parallel would have an equivalent resistance of 4 Ω.

$$R_t = \frac{12}{3} = 4\,\Omega$$

The three 12 Ω resistors in parallel could be replaced with a single 4 Ω resistor.

Similarly, the equivalent resistance of two 10 Ω resistors placed in parallel would be 5 Ω.

POWER IN PARALLEL CIRCUITS

A particular combination of resistors will use different amounts of power depending on whether the resistors are wired in series or parallel. In general, resistors in parallel circuits will draw more current than resistors in series circuits, so parallel circuits use more power than series circuits containing the same resistors.

Recall from Module 5.2 that the power equation is:

$$P = VI$$

By combining this equation with Ohm's law, $V = IR$, the power equation can be written as:

$$P = I^2R$$

These equations can also be used with parallel circuits to find the power dissipated by the entire circuit or by individual components. Here, R_t is the equivalent resistance of the parallel resistors, calculated using:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

Note that you could also combine Ohm's law with the power law to represent it in terms of V and R:

$$P = VI = V \times \frac{V}{R} = \frac{V^2}{R}$$

All three representations of the power equation will give you the same result. It can be helpful to test this out, so give it a go.

Worked example 5.3.3

COMPARING POWER IN SERIES AND PARALLEL CIRCUITS

Consider a 100.0Ω and a 300.0Ω resistor wired in parallel with a 12.0V cell.

a Calculate the total power of the parallel circuit.

Thinking	Working
Calculate the equivalent resistance for the parallel circuit.	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$ $\frac{1}{R_t} = \frac{1}{100.0} + \frac{1}{300.0}$ $= \frac{3}{300.0} + \frac{1}{300.0}$ $= \frac{4}{300.0}$ $R_t = \frac{300.0}{4}$ $= 75.00\,\Omega$
Calculate the total current drawn by the parallel circuit. Rearrange $V = IR$.	$I = \frac{V}{R}$ $= \frac{12.0}{75.0}$ $= 0.160\,A$
Use the power equation to calculate the total power of the parallel circuit.	$P = VI$ $= 12.0 \times 0.160$ $= 1.92\,W$

b Calculate the total power of the circuit if the same two resistors are wired in series.

Thinking	Working
Calculate the equivalent resistance for the series circuit.	$R_t = R_1 + R_2 + \ldots + R_n$ $= 100.0 + 300.0$ $= 400.0\,\Omega$
Calculate the total current drawn by the series circuit. Rearrange $V = IR$.	$I = \frac{V}{R}$ $= \frac{12.0}{400.0}$ $= 0.0300\,A$
Use the power equation to calculate the total power of the series circuit.	$P = VI$ $= 12.0 \times 0.030$ $= 0.360\,W$

c Compare the total power of the circuit for the same two resistors when wired in parallel and in series.

Thinking	Working
Compare the power of the two circuits.	$\frac{P_{parallel}}{P_{series}} = \frac{1.92}{0.360}$ $= 5.33$ The total power of the parallel circuit is 5.33 times greater than that of the series circuit.

➤ Try yourself 5.3.3

COMPARING POWER IN SERIES AND PARALLEL CIRCUITS

Consider a 200.0Ω and an 800.0Ω resistor wired in parallel with a 12.0V cell.

a Calculate the total power of the parallel circuit.

b Calculate the total power for the circuit if the same two resistors are wired in series.

c Compare the total power of the circuit for the same two resistors when wired in parallel and in series.

Parallel circuits in the home

All household appliances and lights are connected in parallel. This is done for two reasons. Figure 5.3.3 shows a television, an air-conditioner, a heater and a washing machine connected in series. Each device is designed to operate at 240V.

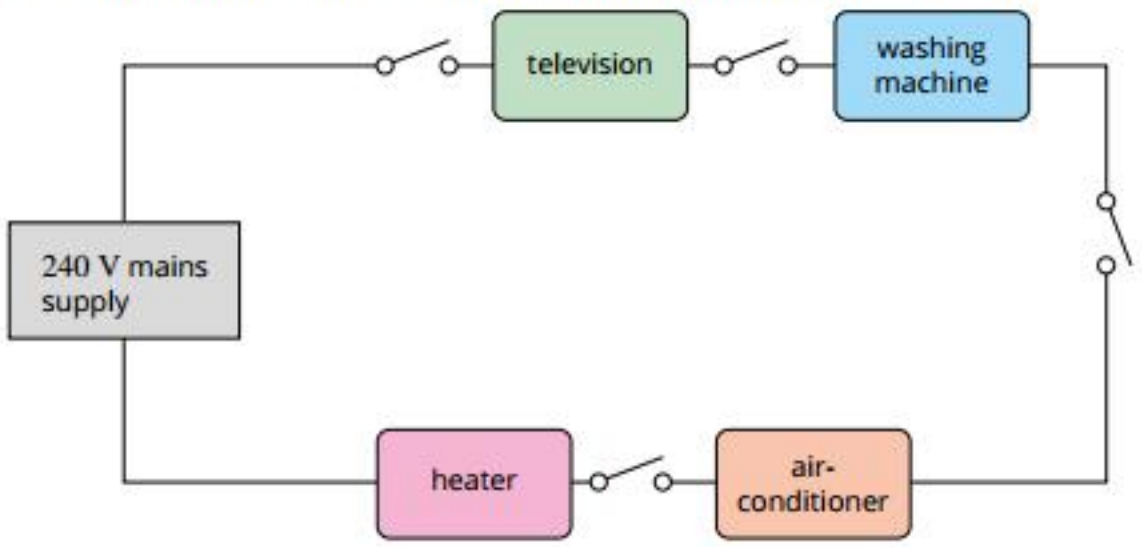


FIGURE 5.3.3 Household appliances connected in series.

A circuit designed like the one in Figure 5.3.3 poses many problems. First, all the devices need to be switched on for the circuit to operate. Second, the 240V supplied to the circuit needs to be shared among all the components. Each component in the circuit would receive far less than the 240V they require to operate. Also, as more and more devices are added to the circuit, the share of the 240V would become smaller. This system could never be practical.

The circuit diagram in Figure 5.3.4 shows the same devices connected in parallel.

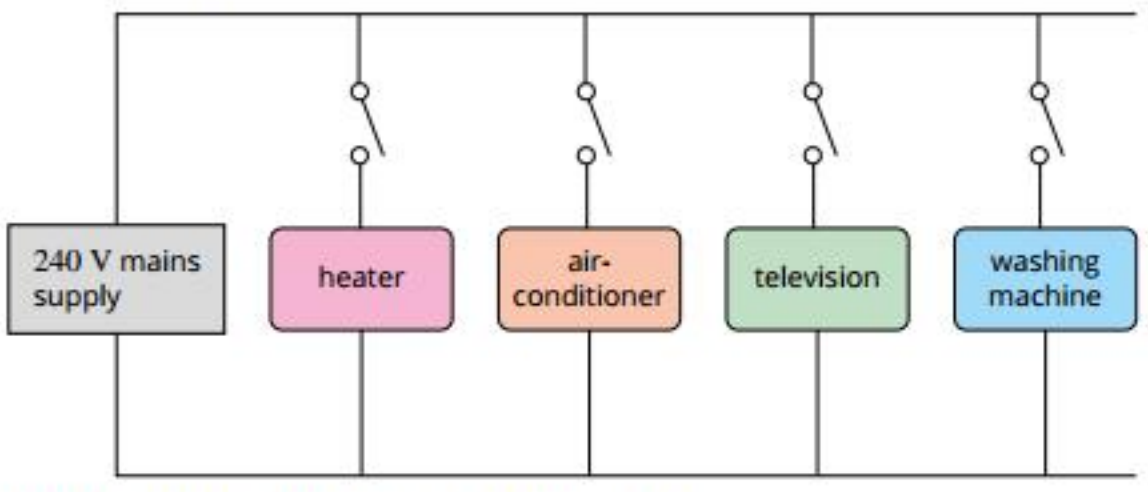


FIGURE 5.3.4 Household appliances connected in parallel.

Each device in the parallel circuit receives the same voltage, 240V. Each device can be independently switched on or off without affecting the others, and more devices can be added to this system without affecting the operation of the devices already connected.

Sometimes the different features of series and parallel circuits can be used to control appliances used in the home. For example, simple heaters of various sorts often have a 'three heat' switch. An electric blanket will usually have 'low', 'medium' and 'high' settings (Figure 5.3.5). Rather than making three different heating elements, the manufacturer can use two elements in different series and parallel combinations to obtain the three heat settings. If the two elements are placed in series (the low setting), the power will be a minimum. For the medium setting, one of the elements will be used by itself. The high setting is then achieved by placing both elements in parallel so that the power will be a maximum.

To determine the relative power being used for each of the three settings, start by comparing the equivalent resistance of each circuit. If it is assumed that the resistance of both elements is the same (R) and does not change appreciably with temperature, the equivalent resistance in the three cases will be given by:

Low heat (two elements in series):

$$R_t = R + R = 2R$$

Medium heat (one element only):

$$R_t = R$$

High heat (both in parallel):

$$R_t = \frac{1}{2}R$$

For a constant potential difference, V, the power is inversely proportional to the resistance, $\left(P = \frac{V^2}{R}\right)$. So, if the high setting is 100%, then the medium setting is 50% and the low setting is 25%.

For example, in the set-up shown in Figure 5.3.5, the following circuits are used to obtain the various settings:

OFF Not connected to power

• Resistors connected in series, $R = 960\,\Omega$, $I = 0.25\,\text{A}$, $P = 60\,\text{W}$

•• Only one element is connected, $R = 480\,\Omega$, $I = 0.5\,\text{A}$, $P = 120\,\text{W}$

••• Resistors connected in parallel, $R = 240\,\Omega$, $I = 1.0\,\text{A}$, $P = 240\,\text{W}$

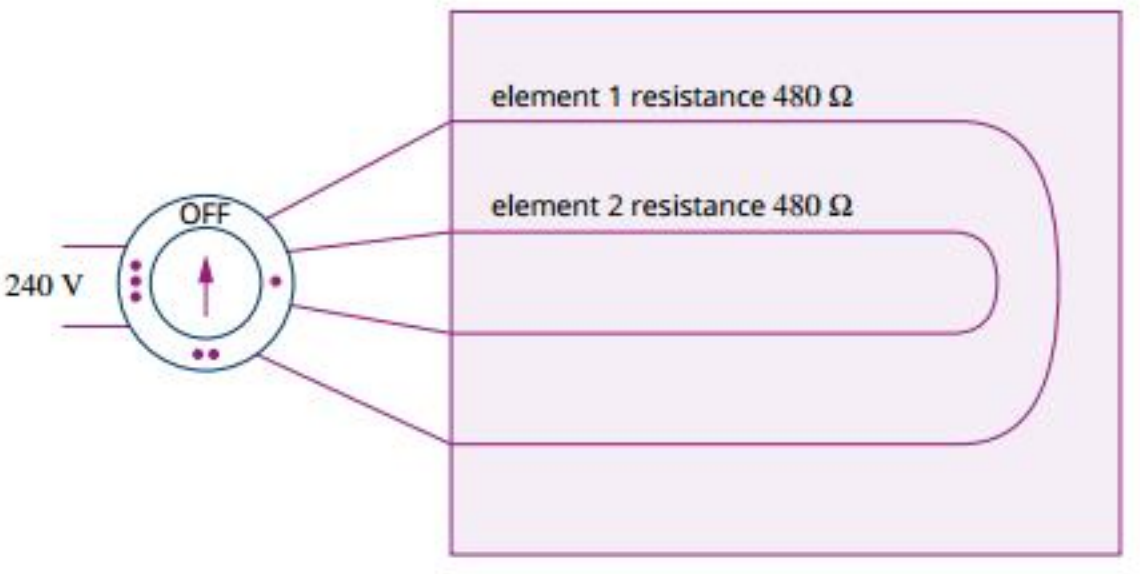


FIGURE 5.3.5 An example of the use of series and parallel combinations of resistors to achieve three heat settings for an electric blanket

5.3 Review

SUMMARY

- Parallel circuits allow individual components to be switched on and off independently.
- When resistors are connected in parallel, the:
  - voltage across each branch of the circuit is the same
  - current is shared between the branches of the circuit, where
    $I_t = I_1 + I_2 + I_3 + \ldots + I_n$
  - equivalent resistance is given by the equation:
$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$
- Ohm's law can be applied to calculate the current drawn by a group of resistors connected in parallel:
$$I = \frac{V_{supply}}{R_t}$$
- The total power drawn by a parallel circuit is larger than that drawn by a series circuit with the same resistors.
- Power supplied to a parallel circuit or dissipated by a component can be calculated using any of the following equations:
$$P = VI$$
where P is the power, V is the potential difference and, I is the current
$$P = I^2R$$
where P is the power, I is the current and R is the resistance
- Power can be dissipated across components in a parallel circuit, as in a series circuit, when energy is transformed.

KEY QUESTIONS

Describe

1 State two reasons why household circuits are wired in parallel.

2 List three variations of the power equation.

Apply

3 Max connects two identical resistors in parallel. Determine whether the equivalent resistance of this set of resistors is the same as, greater than or smaller than the individual resistance of a single resistor.

Analyse

4 Two identical resistors are connected in parallel and are found to have an equivalent resistance of 68.0Ω. Calculate the resistance of each resistor.

5 A 20.0Ω resistor and a 10.0Ω resistor are connected in parallel to a 5.0V battery.
- **a** Calculate the current drawn from the battery.
- **b** Calculate the current flowing through the 20.0Ω resistor.
- **c** Calculate the current flowing through the 10.0Ω resistor.

6 A 40.0Ω resistor and a 60.0Ω resistor are connected in parallel to a battery, with 300.0mA flowing through the 40.0Ω resistor.
- **a** Calculate the voltage of the battery.
- **b** Calculate the current flowing through the 60.0Ω resistor.

7 Two resistors, R_1 and R_2, are connected in parallel to a battery supplying 15V:
$R_1 = 10.0\Omega$
$R_2 = 5.0\Omega$
- **a** Calculate the total power of the circuit.
- **b** Calculate the power dissipated across each resistor.

8 Describe why the power output of a parallel circuit is generally larger than that of a series circuit with the same potential difference and individual resistors.

9 Two resistors are connected in parallel to a cell supplying 15V:
$R_1 = 30\Omega$
$R_2 = 45\Omega$
Calculate the power dissipated across each resistor using the equation:
- **a** $P = I^2R$
- **b** $P = VI$
- **c** $P = \frac{V^2}{R}$

10 Two resistors are connected in parallel to a cell supplying 12V. The resistance of R_1 is unknown and the resistance of R_2 is 36Ω. The total power of the circuit is 24W.
- **a** Calculate the current in the circuit.
- **b** Determine the resistance of R_1.

5.4 Circuit laws and complex circuit analysis

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- analyse complex circuits containing series and parallel components
- understand circuit laws about potential difference and current in a circuit
- explain the conservation of charge and the conservation of energy in electric circuits
- apply the current law and voltage law to check your calculations for complex circuits.

COMPLEX CIRCUIT ANALYSIS

In Chapter 4, you learnt that Ohm's law, $V = IR$, can be used to relate the voltage and current in a simple circuit with a single resistor of resistance R. As you have already seen in this chapter, when a circuit contains more than one resistor, Ohm's law alone is not sufficient to predict the current flowing through, and the potential difference across, each resistor.

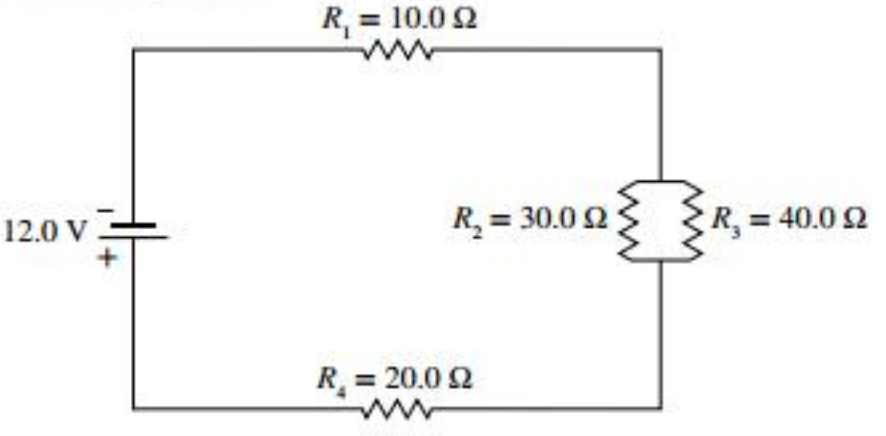
However, no matter how complex the circuit, it can always be divided up into sections of series and parallel circuits, which can be analysed using the equations from Modules 5.2 and 5.3.

Some circuits combine elements of both series wiring and parallel wiring. A general strategy for analysing these circuits is to reduce the complex circuit to a single equivalent resistance to determine the current drawn by the circuit. It is then possible to step back through the process of simplification to analyse each section of the circuit as needed.

Worked example 5.4.1

COMPLEX CIRCUIT ANALYSIS

Consider the following circuit:

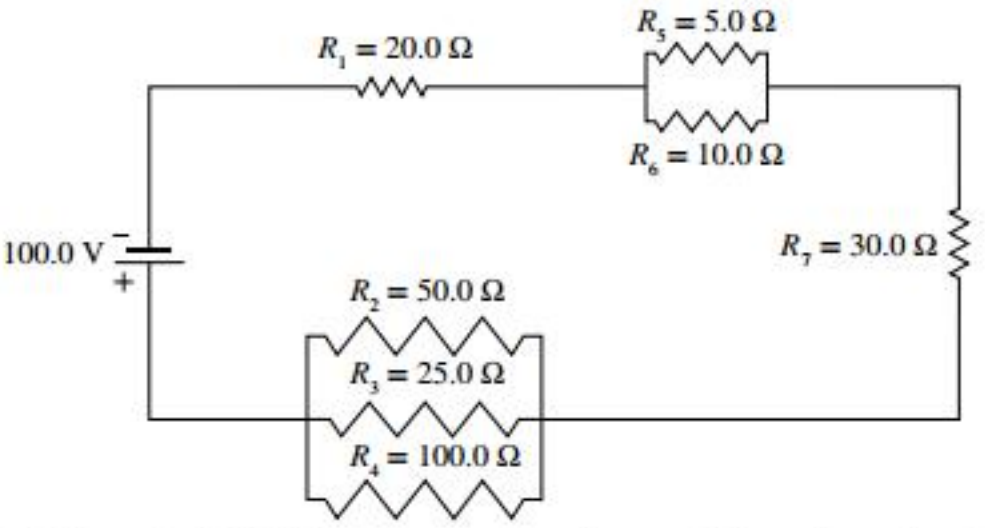


Thinking	Working
a Calculate the potential difference across, and current through, each resistor in the circuit.	
Find an equivalent resistance for the parallel resistors. The equivalent resistance of these should be less than the resistance of the smaller resistor, that is, smaller than 30.0Ω.	$\frac{1}{R_{2\text{-}3}} = \frac{1}{R_2} = \frac{1}{R_3}$ $= \frac{1}{30.0} + \frac{1}{40.0}$ $= \frac{4}{120.0} + \frac{3}{120.0}$ $R_{2\text{-}3} = \frac{120.0}{7}$ $= 17.1\,\Omega$
Find an equivalent series resistance for the circuit, as the circuit can now be thought of as three resistors in series: 10.0Ω, 17.1Ω and 20.0Ω.	$R_t = 10.0\,\Omega + 17.1\,\Omega + 20.0\,\Omega$ $= 47.1\,\Omega$
Use Ohm's law to calculate the current in the circuit. Use the supply voltage and total resistance to do this calculation. Rearrange $V = IR$.	$I = \frac{V}{R}$ $= \frac{12.0}{47.1}$ $= 0.255$ A
Use Ohm's law to calculate the potential difference across each resistor (or parallel group of resistors) in series. (Note that the potential difference across R_2 is the same as that across R_3 as they are in parallel.)	$V = IR$ $V_1 = 0.255 \times 10.0 = 2.55$ V $V_{2\text{-}3} = 0.255 \times 17.1 = 4.36$ V $V_4 = 0.255 \times 20.0 = 5.09$ V
Use Ohm's law where necessary to calculate the current through each resistor.	$I_1 = I_4 = 0.255$ A $I = \frac{V}{R}$ $I_2 = \frac{4.36}{30.0} = 0.145$ A $I_3 = \frac{4.36}{40.0} = 0.109$ A
b Calculate the total power of the circuit and the power dissipated across each resistor.	
Calculate the total power of the circuit. Make sure to use the supplied voltage and the circuit current.	$P = VI$ $= 12.0 \times 0.255$ $= 3.06$ W
Calculate the power dissipated across each resistor using either $P = VI$ or $P = I^2R$. Make sure to use the voltage drop, current or resistance associated with each individual resistor.	$P_1 = I_1^2R_1$ $= 0.255^2 \times 10.0$ $= 0.648$ W $P_2 = I_2^2R_2$ $= 0.145^2 \times 30.0$ $= 0.635$ W $P_3 = I_3^2R_3$ $= 0.109^2 \times 40.0$ $= 0.476$ W $P_4 = I_4^2R_4$ $= 0.255^2 \times 20.0$ $= 1.30$ W
c Compare the total power of the circuit to the power dissipated across each resistor.	
The total power of the circuit is equal to the sum of the power dissipated across each resistor. This is confirmed by the law of conservation of energy; that is, no energy is lost during any energy transformation.	$P_t = P_1 + P_2 + P_3 + P_4$ $= 0.648 + 0.635 + 0.476 + 1.30$ $= 3.06$ W

➤ Try yourself 5.4.1

COMPLEX CIRCUIT ANALYSIS

Consider the following circuit.



a Calculate the potential difference across, and current through, each resistor in the circuit.

b Calculate the total power of the circuit and the power dissipated across each resistor.

c Compare the total power of the circuit to the power dissipated across each resistor.

CIRCUIT LAWS

FIGURE 5.4.1 Gustav Kirchhoff discovered the rules that underpin our understanding of how electrical circuits work.

German physicist Gustav Kirchhoff (1824–87), shown in Figure 5.4.1, formulated two laws to describe the behaviour of current and potential difference in a circuit. These are useful for analysing current and potential difference in complex circuits.

Kirchhoff also made important contributions in the fields of spectroscopy, thermochemistry and the study of black-body radiation. He worked with Robert Bunsen, the German chemist who developed the Bunsen burner.

The voltage law

The **voltage law of circuits** (sometimes called Kirchhoff's voltage law or Kirchhoff's loop rule) tells you that the sum of the potential differences across all the elements around any closed circuit loop must be zero. This means that the total potential drop around a closed circuit must be equal to the total potential gain in the circuit. For example, if a battery provides 9 V to a circuit, then the sum of all of the potential drops across the components must add to 9 V.

This rule is essentially another version of the law of conservation of energy.

The potential gain (for example, the voltage supplied by the battery) is equal to the potential drop across the circuit. So for n components in a circuit:

$$V_{\text{supply}} = V_t = V_1 + V_2 + \ldots + V_n$$

If you apply a sign convention to the change in potential so that a potential gain is positive and a potential drop is negative, then the positive and negative values will cancel. You can write the voltage law using the 'sum of' symbol (Σ). This means that the sum of the changes in potential will be zero.

$$\Sigma \Delta V = 0$$

i The energy given to each charge (potential gain) must be equal to the energy lost by each charge (potential drop).

In a series circuit, the energy loss will be spread across a number of different components.

In a parallel circuit, the energy loss (potential drop) will be the same across each of the parallel components.

Figure 5.4.2 shows how the voltage provided by the battery is shared across a resistor and a lightbulb connected in series.

The energy changes in this circuit can be visualised in several ways. In Chapter 4 and Module 5.3, the analogy was used of the charges as water being pumped around an elevated watercourse. The water gains potential energy as it is pumped higher, and as it flows back down the potential energy is converted into other forms. The diagram in Figure 5.4.3 shows how the analogy works with the energy changes that occur in a circuit. The battery acts as a 'pump' that pushes electrons up to a higher energy level and the electrons gain potential energy. As the electrons pass down through components in the circuit, their energy is transformed into other forms.

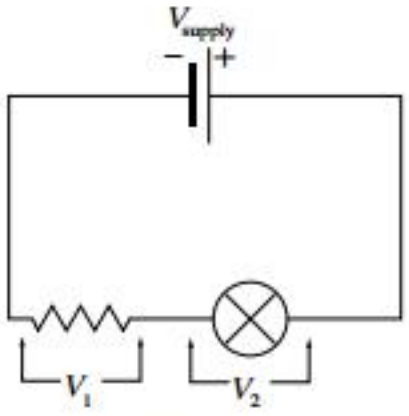


FIGURE 5.4.2 The voltage law of circuits: $(V_1 + V_2)$ is $= V_{supply}$

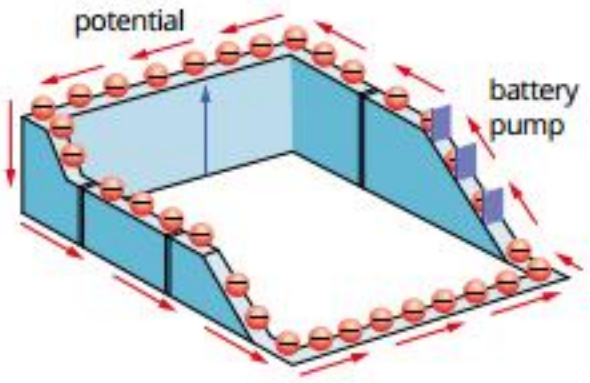


FIGURE 5.4.3 An analogy for analysing a circuit

The change in electrical potential energy available to electrons can also be represented graphically, as shown in Figure 5.4.4. Some of this energy is lost as the electrons pass through the resistor. The remaining energy is lost as the electrons pass through the lightbulb. In this circuit, the lightbulb has more resistance than the resistor. The potential energy provided by the cell, V_{supply}, is the same as the sum of the potential drop across the resistor, V_1, and the potential drop across the lightbulb, V_2.

Recall from Module 5.3 that in a parallel circuit the voltage (potential drop) across the parallel components is the same: the voltage across resistor R_1 is the same as the voltage (potential drop) across resistor R_2. Figure 5.4.5 shows that electrons at points B and D will have the same energy as they have when they leave the negative battery terminal; that is, the potential at points B and D is the same as it is at the negative battery terminal. The potential at points A and C is also the same as the potential at the positive battery terminal. Therefore, the potential drop across each resistor is the same.

If $R_1 \neq R_2$, then a different current will flow along each branch of the parallel part of the circuit, but the potential across each resistor will be the same. Using the water analogy from Figure 5.4.3, the water reaches the same height and falls the same distance, but the amount of water flowing in each path will vary depending on the size of the course it flows along.

You might assume that wires ideally have zero resistance so that the potential at B and D will be the same, but in fact the wires will have a very small resistance so that the potential at B and D will be slightly different. However, this is such a small difference that you do not need to take it into account in your calculations. It only becomes significant when long lengths of wire are used, such as in power lines.

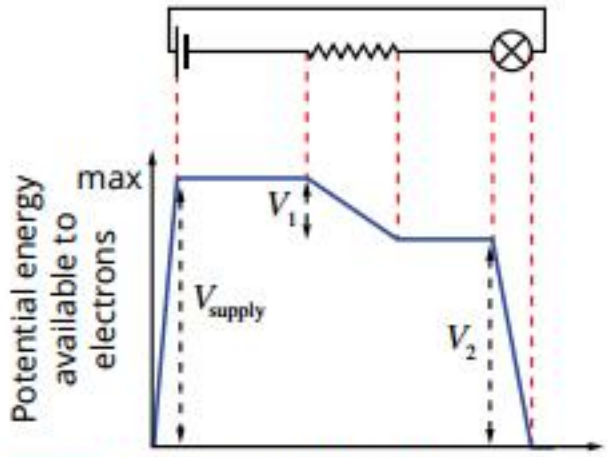


FIGURE 5.4.4 The electrical potential energy of an electron changes as it moves around the circuit.

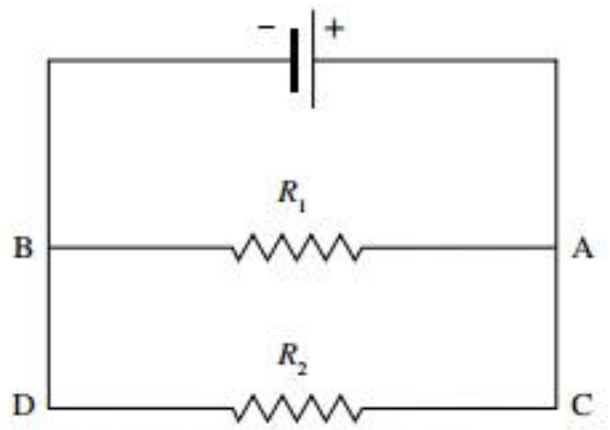


FIGURE 5.4.5 In a parallel circuit, the potential at points B and D is the same as the potential at the negative battery terminal. The potential at points A and C is the same as the potential at the positive battery terminal.

Worked example 5.4.2

APPLYING THE VOLTAGE LAW

A 12.0V battery is connected in series to a 100.0Ω resistor and a 300.0Ω resistor.

a Determine the equivalent resistance of the two resistors.

Thinking	Working
The equivalent resistance of two resistors in series: $R_t = R_1 + R_2$	$R_t = 100.0 + 300.0$ $= 400.0\,\Omega$

b Calculate the potential difference across each resistor, using Ohm's law.

Thinking	Working
Use Ohm's law to find the current in the circuit. Rearrange $V = IR$.	$I = \frac{V}{R}$ $= \frac{12.0}{400.0}$ $= 0.0300\,A$
Calculate the potential difference across the 100.0Ω resistor.	$V = IR$ $= 0.030 \times 100.0$ $= 3.00\,V$
Calculate the potential difference across the 300.0Ω resistor.	$V = IR$ $= 0.030 \times 300.0$ $= 9.00\,V$

c Apply the voltage law to verify your answers.

Thinking	Working
Use the voltage law: $V_{supply} = V_t = V_1 + V_2 + \ldots + V_n$	In a series circuit: $V_{supply} = V_{100} + V_{300}$ $12.0 = 3.0 + 9.0$ The voltage law holds, so the answers for the potential difference across each resistor are correct.

➤ Try yourself 5.4.2

APPLYING THE VOLTAGE LAW

A 10.0V battery is connected in series with two 50.0 Ω resistors.

a Determine the equivalent resistance of the two resistors.

b Calculate the potential difference across each resistor, using Ohm's law.

c Apply the voltage law to verify your answers.

The current law

Parallel circuits involve **junctions** at which current can flow in a variety of directions. **The current law of circuits** (sometimes called Kirchhoff's current law or Kirchhoff's junction rule) predicts the behaviour of current at these points. The current law tells you that the total amount of current flowing into a junction must be the same as the total current flowing out of the junction.

The current law is just an extension of the idea of conservation of charge, that charges cannot be created or destroyed. Although the number of electrons flowing into a junction might be very large, electrons are not created or destroyed in the junction, so the same number of electrons must flow out again. This is illustrated in Figure 5.4.6. The current law explains how current splits in a parallel circuit. It explains why the current in the main part of the circuit is the sum of the currents in each parallel branch.

This is shown in the circuit diagram in Figure 5.4.7, where $I_t = I_1 + I_2 + I_3$.

If you apply a sign convention such that the current into a junction is positive and the current flowing out of a junction is negative, then the positive and negative values will cancel. You can write this using the 'sum of' symbol Σ. This means that the sum of the current through a junction will be zero.

$$\Sigma I = 0$$

> **i** The total amount of current flowing into a junction must be the same as the total current flowing out of the junction.

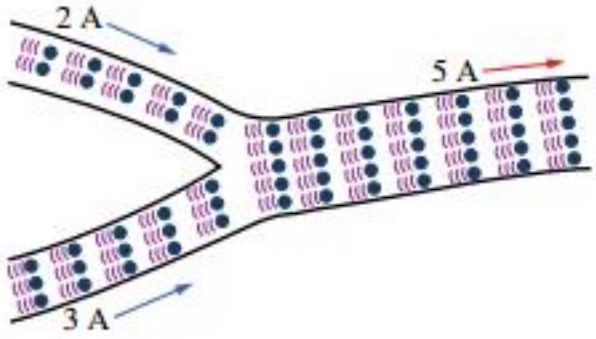


FIGURE 5.4.6 The current flowing into any junction must be equal to the current flowing out of it.

Worked example 5.4.3

APPLYING THE CURRENT LAW

In the circuit shown in Figure 5.4.7, a 10.0V battery is connected to three resistors in parallel. The equivalent parallel resistance of the three resistors is 20.0Ω. The branch currents are $I_1 = 0.1$ A and $I_2 = 0.2$ A. Calculate the branch current I_3 using the current law of circuits.

Thinking	Working
First find I_t, the current in the main part of the circuit.	$I_t = \frac{V}{R}$ $= \frac{10.0}{20.0}$ $= 0.500\,\text{A}$
Use the current law to find the branch current I_3.	$I_t = I_1 + I_2 + I_3$ $I_3 = I_t - I_1 - I_2$ $= 0.500 - 0.1 - 0.2$ $= 0.2\,\text{A}$

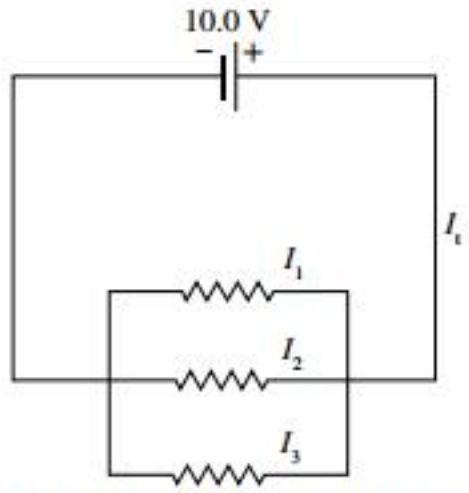


FIGURE 5.4.7 The current flowing into any junction must be equal to the current flowing out of it.

➤ Try yourself 5.4.3

APPLYING THE CURRENT LAW

In the circuit shown in Figure 5.4.7, the 10.0V battery is replaced with a 9.0V battery. The equivalent parallel resistance of the three resistors is 30.0Ω. The branch currents are $I_1 = 0.1$ A and $I_2 = 0.1$ A. Calculate the branch current I_3 using the current law of circuits. Explain what you can deduce about the three resistors from this.

5.4 Review

SUMMARY

- The current law of circuits states that the total amount of current flowing into a junction must be the same as the total current flowing out of the junction. At each junction, $\Sigma I = 0$.
- The voltage law of circuits states that the energy given to the charges (potential gain) must be equal to the energy lost by the charges (potential drop). Across each circuit, $\Sigma \Delta V = 0$.
- In a series circuit, the energy loss (potential difference) will be spread across a number of different components.
- In a parallel circuit, the energy loss (potential difference) will be the same across each of the parallel components.

KEY QUESTIONS

Describe

1 Complete the following sentence by selecting the correct term from the terms in brackets.

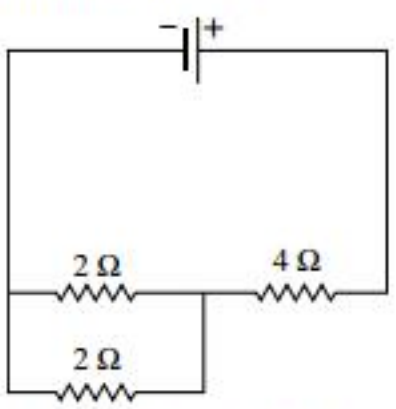
The voltage law of circuits states that the sum of the potential drops [at a junction/across a circuit] must equal the total potential gain in the circuit.

2 Complete the following sentence by selecting the correct term from the terms in brackets.

The current law of circuits states that the total current output at a junction must equal [the sum of the current inputs/half of the current input].

Apply

3 Gary connects two 2Ω resistors in parallel, and then connects another 4Ω resistor in series, as shown. To work out the equivalent resistance of the circuit, he adds up the resistance of each resistor to make an equivalent resistance of 8Ω.

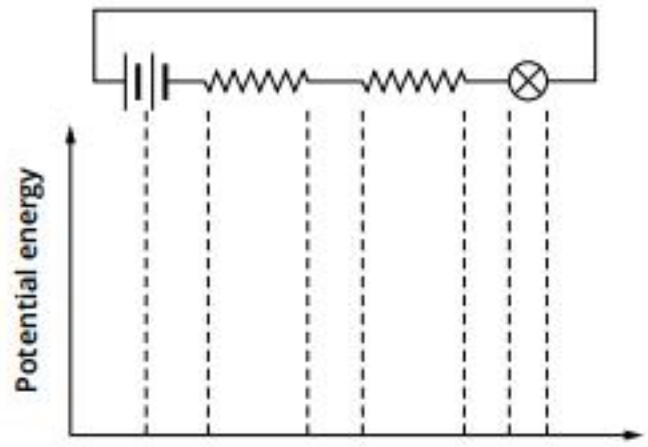


a Determine if Gary is correct. If he is not correct, describe how he should calculate the equivalent resistance of the circuit.

b Susan says that the current law of circuits states that the current flowing in Gary's circuit is the same at every point. Determine if she is correct. If not, explain how she is incorrect.

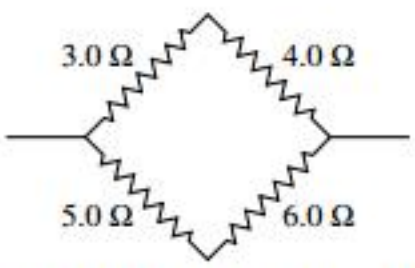
4 Describe how the law of conservation of energy applies to electrical circuits.

5 Copy and complete this graph to describe the changes in potential energy across each component in the circuit shown.



Analyse

6 A circuit contains four resistors as shown in the diagram.



a Calculate the equivalent resistance of this combination of resistors.

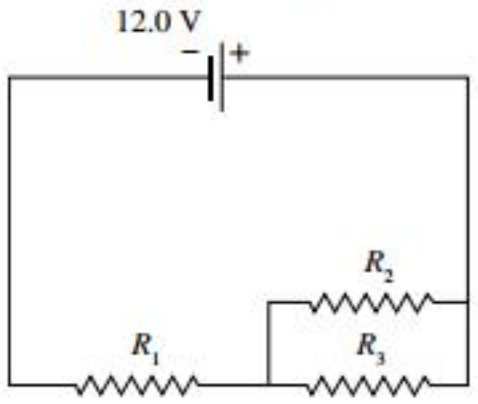
b If a 10.0V battery is connected to this set of resistors, calculate the total current flowing through the circuit, and the current flowing through each branch of resistors.

c Use the current law of circuits to verify your answer to part **b**.

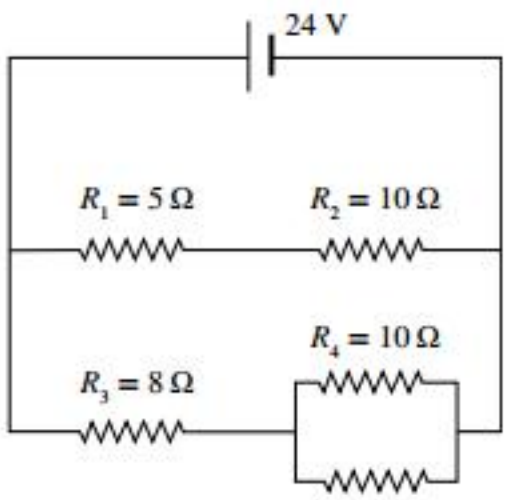
7 For the circuit shown in the diagram, $R_1 = 10.0\,\Omega$, $R_2 = 10.0\,\Omega$ and $R_3 = 15.0\,\Omega$.

a Calculate the potential difference across resistor R_2.

b Calculate the current through resistor R_3.



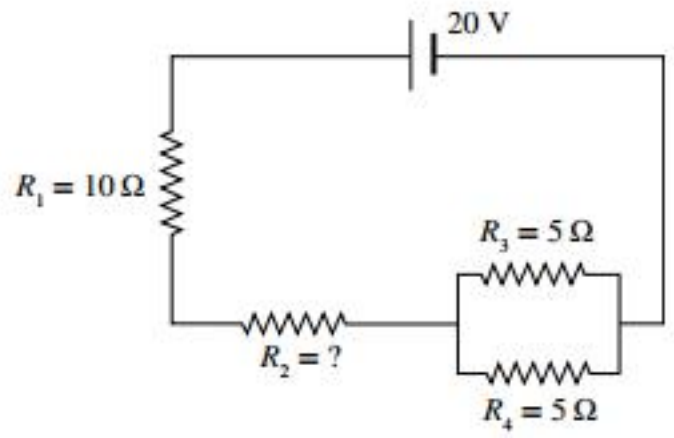
8 Consider the following circuit:



a Calculate the total equivalent resistance in the circuit and hence the current in the circuit.

b Calculate the potential difference across, and current through, each resistor in the circuit.

9 Consider the following circuit where the total power of the circuit is 30 W:



a Calculate the current in the circuit.

b Determine the resistance of R_2.

Chapter review

05

KEY TERMS

current law of circuits
electrical circuit
equivalent resistance
internal resistance
junction
law of conservation of electric charge
multimeter
parallel circuit
series circuit
voltage law of circuits

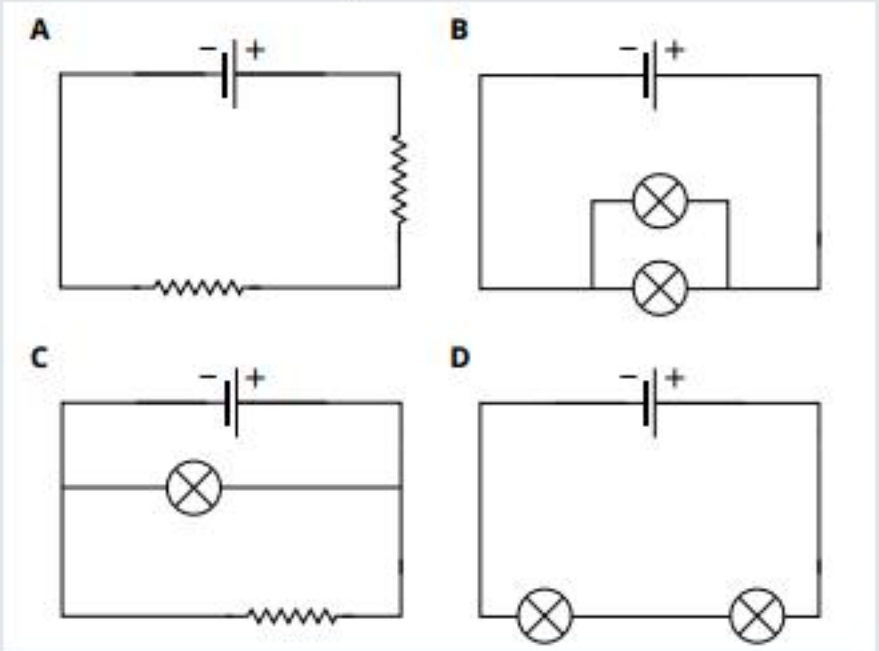
KEY QUESTIONS

Describe

1 Identify which of the following conditions is necessary for current to flow in a circuit. More than one correct answer is possible.

A There must be a voltage applied across the circuit.
B The circuit must contain a resistor.
C The circuit must be a closed loop.
D The circuit must be an open loop.

2 Identify which of these circuits are wired in series, and which are wired in parallel.



3 Two resistors, R_1 and R_2, are wired in series. Identify which of the following gives the equivalent series resistance for these two resistors.

A $R_t = R_1 + R_2$
B $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$
C $R_t = R_1 - R_2$
D $R_t = R_1 \times R_2$

4 Two resistors, R_1 and R_2, are wired in parallel. Identify which of the following gives the equivalent parallel resistance for these two resistors.

A $R_t = R_1 + R_2$
B $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$
C $R_t = R_1 - R_2$
D $R_t = R_1 \times R_2$

5 **a** State the voltage law of circuits.
b State the current law of circuits.

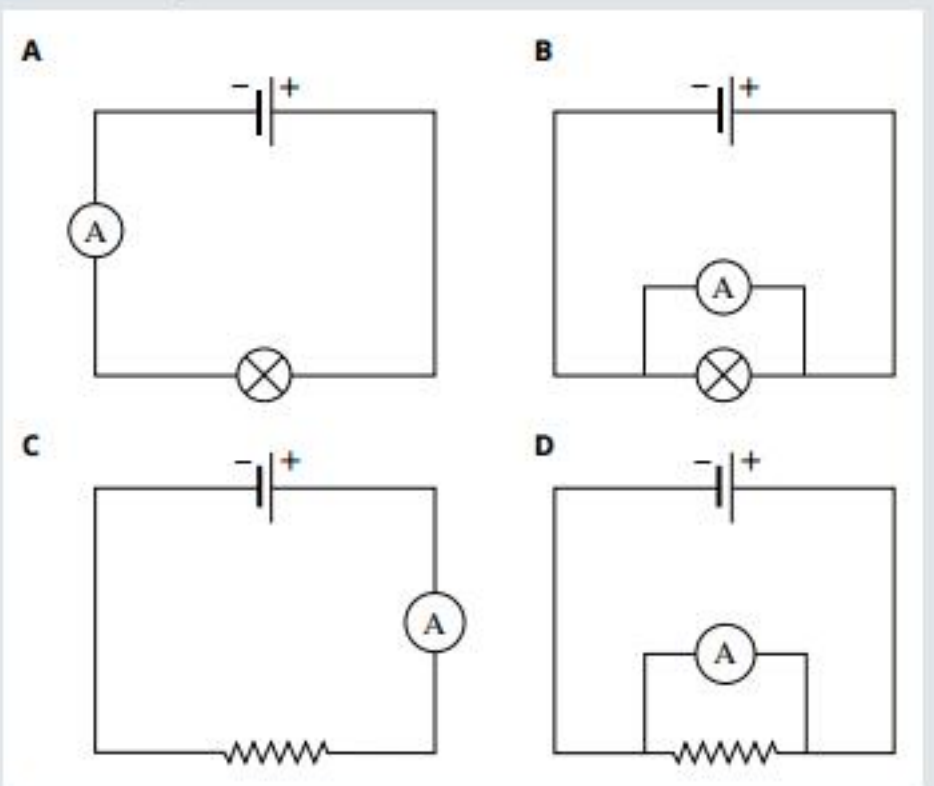
6 Write an equation for the power dissipated across a resistor.

Apply

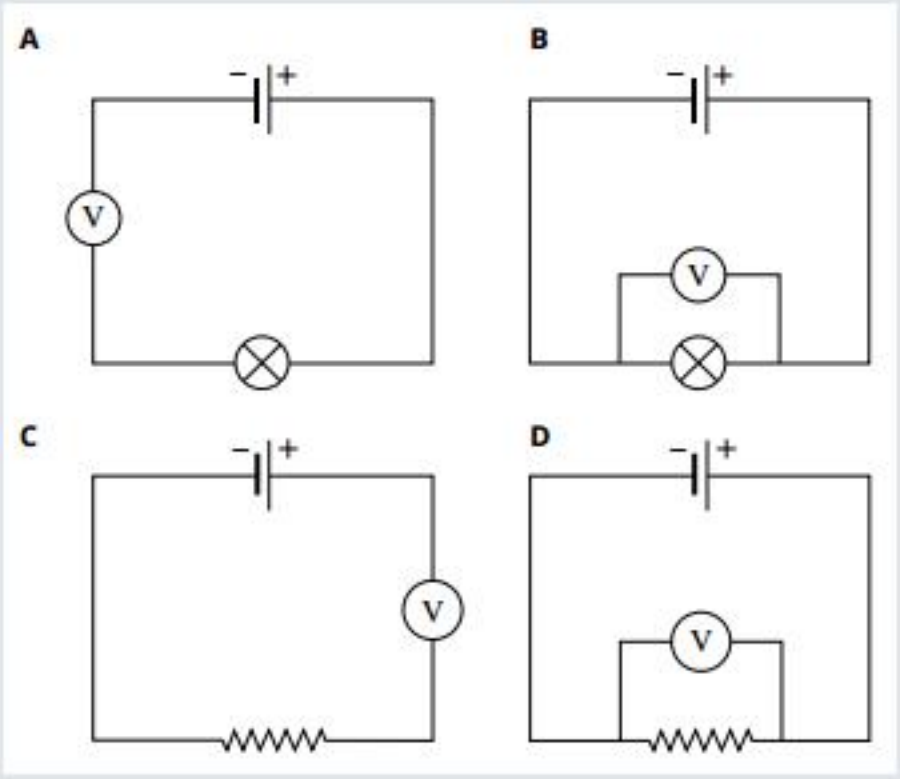
7 Draw a circuit containing a battery, a lightbulb, a resistor and a switch in series. Indicate the direction of conventional current and electron flow.

8 Finn wants to measure the total current flowing to and from a battery in a circuit with a lightbulb.

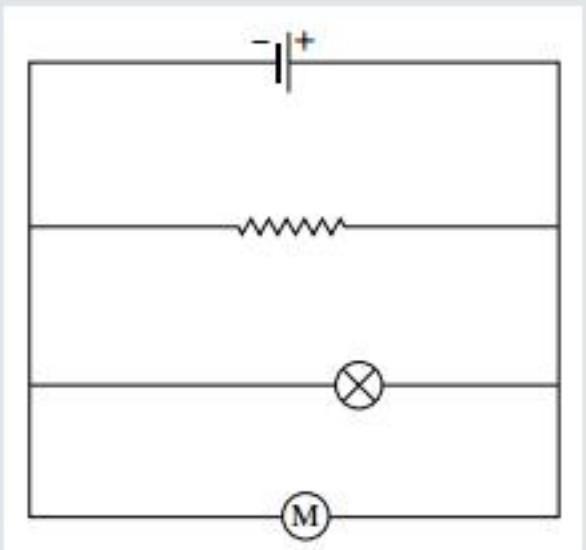
a Identify which of the circuits Finn should use.



b Finn now wants to measure the potential difference over the lightbulb in the circuit. Identify which of the circuits Finn should use.



c When Finn gets to class the circuit shown in the diagram is already set up. Identify whether Finn should set the multimeter, M, to measure current or potential difference and determine what would happen if he chose the other option.



9 Two identical resistors are wired in series. Determine whether you would expect their equivalent series resistance to be the same as, greater than or less than the individual resistance of each of the resistors. Explain your answer.

10 Two identical resistors are wired in parallel. Determine whether you would expect their equivalent parallel resistance to be the same as, greater than or less than the individual resistance of each of the resistors.

11 Kim and Taylor are shopping for a string of exactly 100 lightbulbs for a party. There are two types on offer: Kim wants to buy the set of lights connected in parallel, and Taylor wants to buy the lights connected in series. Identify which is the better choice and explain why.

12 Identify the best definition of power from the following choices.

A the total amount of energy consumed by a circuit component

B the current drawn by a circuit component each second

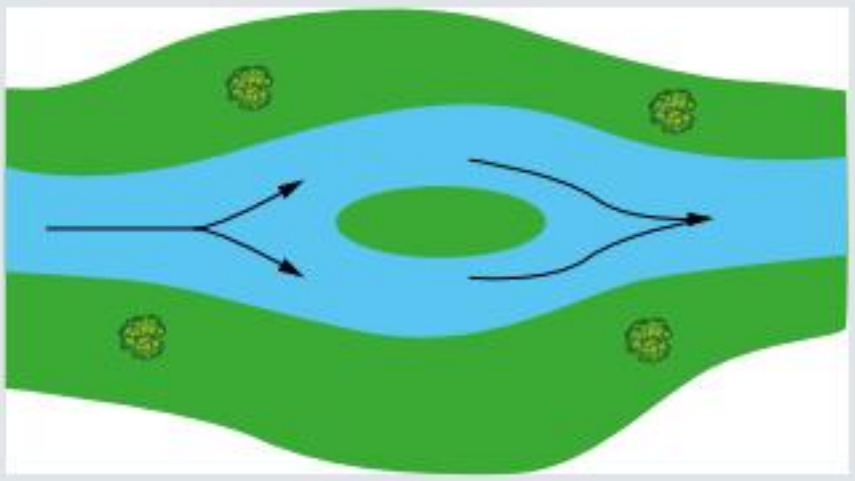
C the rate at which voltage is supplied to a circuit component

D the rate at which energy is transformed by a circuit component

13 The total power supplied by a circuit is 15W. The circuit has two resistors connected in parallel. The power dissipated across the first resistor is 8W. Determine the power dissipated across the second resistor.

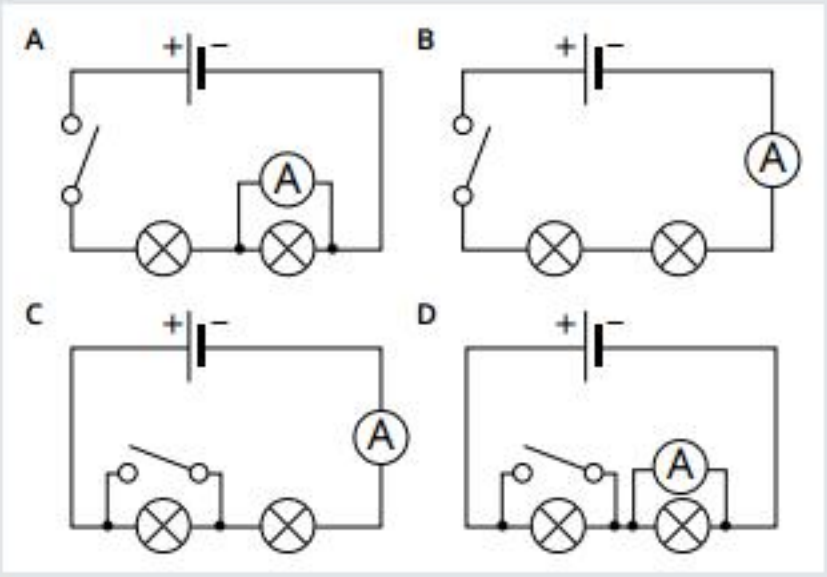
14 Describe the purpose of a resistor's maximum power rating.

15 Compare electric current in a circuit to the following diagram of a stream.



Analyse

16 A student decides to set up a circuit that contains a cell, two lightbulbs and a switch, so that both lightbulbs will light when the switch is closed. She adds an ammeter to measure the current flowing through the lightbulbs. Assess which of the circuits shown below would achieve this.



17 Two resistors are connected in series to a cell supplying 50V. The resistance of R_1 is unknown and the resistance of R_2 is 100Ω. The power supplied to the circuit is 4W. Determine the resistance of R_1.

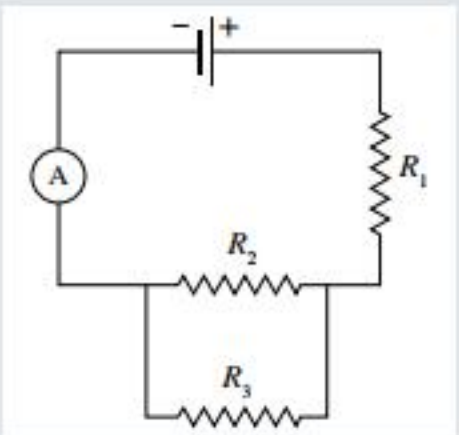
A 50Ω
B 80Ω
C 525Ω
D 625Ω

18 **a** A student accidentally sets up an ammeter in parallel to a lightbulb instead of in series. When the power supply is switched on, the ammeter draws a large current and is damaged. Describe the internal resistance of the ammeter from this information.

b The student, who is not having a very good day, removes the ammeter and sets up a voltmeter in series with the lightbulb. When the power supply is switched on, the lightbulb does not light. Explain why.

19 Three resistors of 2.0Ω, 3.0Ω and 5.0Ω are wired in series. Calculate their equivalent series resistance.

20 A student connects a 10.0V battery in the circuit shown. They measure the reading on the ammeter as 500.0mA.

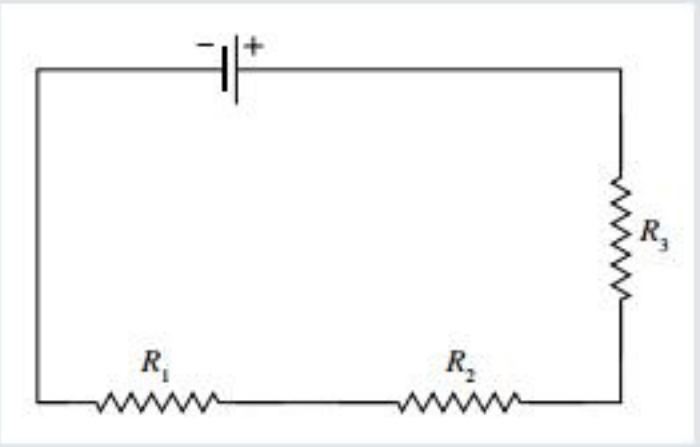


a Calculate the equivalent resistance of resistors R_1, R_2 and R_3.

b Calculate the individual resistances of R_1, R_2 and R_3 if R_2 and R_3 are identical and if the potential difference across R_1 is 5.0V.

c Determine the current, in milliamps, flowing through R_3.

21 In the circuit shown, a 10.0V battery is connected to three resistors in series: $R_1 = 4.0\Omega$, $R_2 = 8.0\Omega$ and $R_3 = 12.0\Omega$.

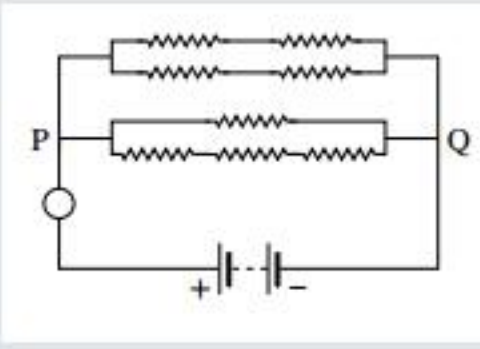


a Calculate the equivalent series resistance of the three resistors.

b Calculate the current flowing in the circuit.

c Calculate the potential difference across each resistor. Use the voltage law to check your answer.

22 In the circuit shown, eight 20.0Ω resistors are connected between points P and Q.

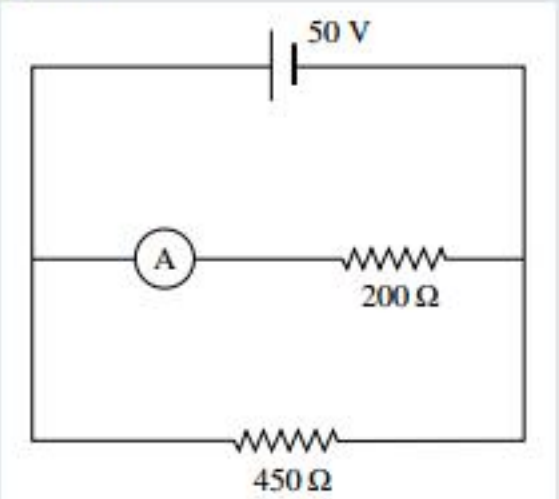


a The circle in the circuit diagram represents either an ammeter or a voltmeter. Identify which type of meter this should be.

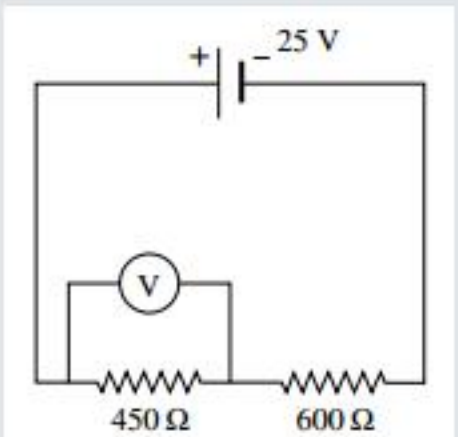
b Calculate the total equivalent resistance of the circuit. Assume that the resistance of the meter and power source can be ignored.

23 Sketch a circuit diagram to show how three 5Ω resistors can be connected in a circuit with 12V of supplied voltage if the current drawn is 7.2A.

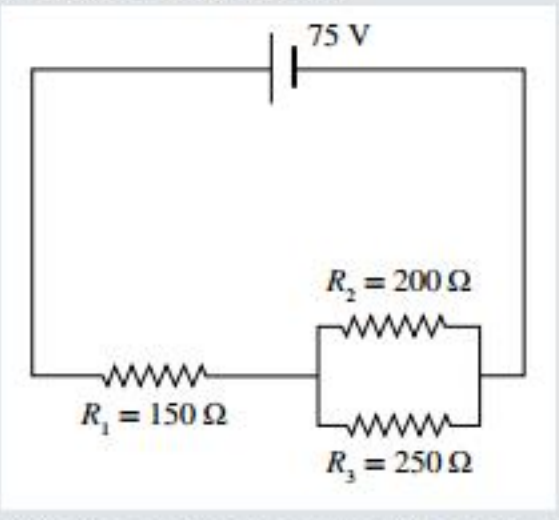
24 Determine the reading on the ammeter in the following circuit:



25 Determine the reading on the voltmeter in the following circuit:



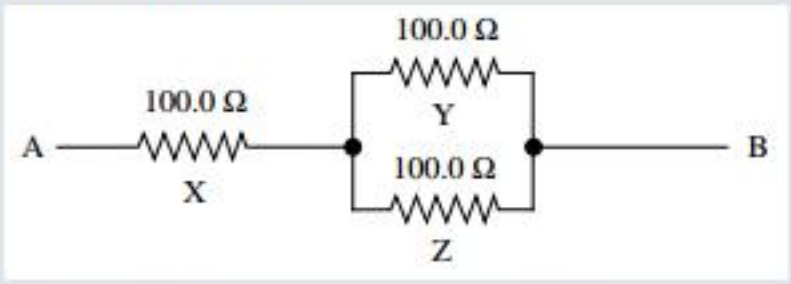
26 Consider the following circuit. Note that R_1 has a maximum power rating of 3 W.



a Calculate the maximum current that can pass through R_1 without causing damage to the resistor.
b Calculate the equivalent resistance of the circuit.
c Calculate the current in the circuit.
d Determine if R_1 is able to transform electrical energy safely into heat energy.

27 A circuit consists of a 12.0 V battery and three 20.0 Ω lightbulbs. The lightbulbs are initially connected in series.
a Calculate the power output of the circuit.
b The circuit is changed so that the lightbulbs are connected in parallel. Calculate the power output of the circuit.
c Compare the power dissipated across the resistors in the parallel circuit with that of the series circuit.

28 Three 100.0 Ω resistors are connected as shown. The maximum power that can safely be dissipated in any one resistor is 25.0 W.



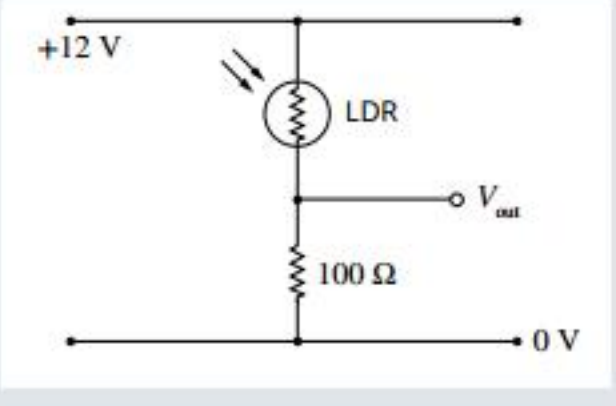
a Determine the maximum potential difference that can be applied between points A and B.
b Determine the maximum power that can be dissipated in this circuit.

29 Four 20.0 Ω lightbulbs are connected to a 10.0 V battery. Determine the total power output of the circuit if the lightbulbs are connected in the following ways.
a in series
b in parallel

30 Imagine you are an electrician tasked with creating the electrical circuit diagrams for a new backyard office space. The office requires three 100 W lightbulbs and a small fridge (inside of which is a resistor with a resistance of 55 Ω), all connected in parallel. There is a switch associated with each component. All components are powered by a solar generator, which produces a DC current at 240 V.
a Construct a circuit diagram to describe this circuit.
b Calculate the equivalent resistance of the circuit.

Interpret

31 A light-dependent resistor (LDR) is a device with a resistance that varies according to the amount of light that hits it. Usually, its resistance is very high in the dark, and decreases as more light hits it. A simple light-detector circuit using an LDR is shown. V_{out} is used to activate an alarm when the ambient light rises above a trigger level. At this trigger level, the resistance of the LDR is 200.0 Ω. The alarm activates whenever V_{out} is above the trigger level.



a Calculate the value of V_{out} at which the alarm would activate.
b Determine what you would expect V_{out} to become when it is very dark.

Data analysis

DATA SET 1

The information below applies to Questions 1–2.

A student has set up a circuit as shown in Figure 1 to investigate the current and voltage laws of circuits in a laboratory. Note that the resistors use a colour band system to show the following assumed values:

$R_1 = 300\Omega \pm 5\%$
$R_2 = 1000\Omega \pm 5\%$
$R_3 = 1500\Omega \pm 5\%$
$R_4 = 2000\Omega \pm 5\%$
$R_5 = 2200\Omega \pm 5\%$

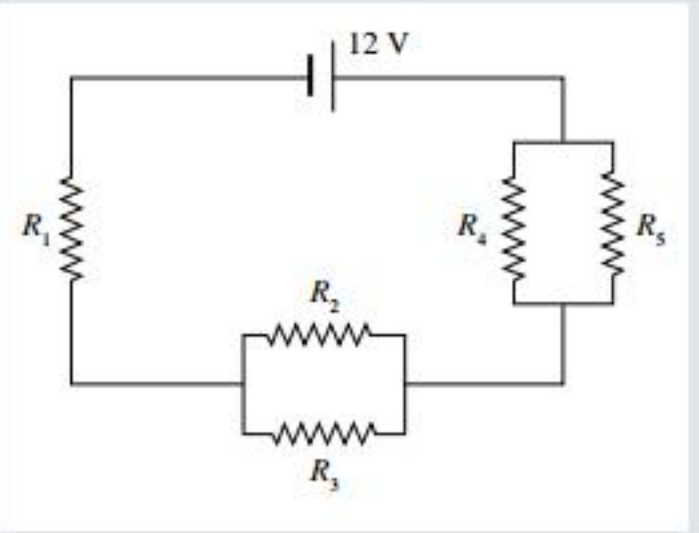


FIGURE 1 Circuit diagram of experimental set-up

Using a multimeter, the voltage and current through each resistor is measured. The experimental data collected is shown in Table 1.

TABLE 1 Measured current and voltage across each resistor

Resistor, resistance (Ω)	Voltage (V) ± 0.005	Current (mA) ± 0.05
$R_1 = 300 \pm 5\%$	1.85	6.2
$R_2 = 1000 \pm 5\%$	3.70	3.7
$R_3 = 1500 \pm 5\%$	3.69	2.5
$R_4 = 2000 \pm 5\%$	6.45	3.2
$R_5 = 2200 \pm 5\%$	6.45	2.9

Question 1 (4 marks)

Verify the voltage law for this experimental set-up.

Question 2 (5 marks)

Verify the current law for this experimental set-up.

REVIEW QUESTIONS

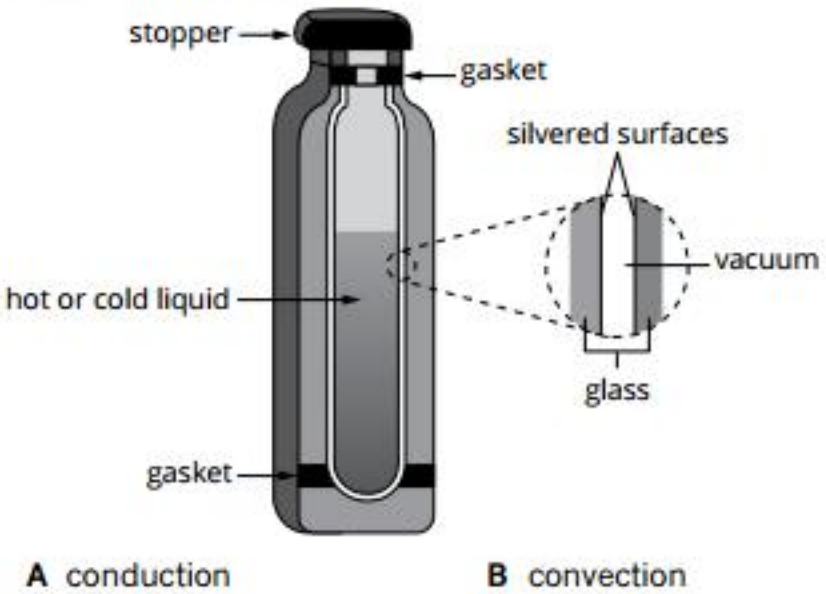
Topic 1: Heating processes

Multiple choice

1 Select which of the following is the best example of heat transfer by conduction.

A heat transfer from the bottom of the ocean to the top
B heat transfer from the Sun to Earth
C heat transfer from Earth's mantle through Earth's crust
D heat transfer from Earth's surface to the upper atmosphere

2 A vacuum flask, or 'thermos', has a reflective coating of aluminium on the internal surface. This 'silvered' surface reduces heat transfer by:



A conduction
B convection
C radiation
D all of the above

3 The name for the property of a substance that determines how much energy it takes to change the temperature of a unit mass of the substance by 1 degree Celsius is:

A refractive index
B emissivity
C albedo
D specific heat capacity

4 Two students were comparing the temperature and internal energy of two beakers of water. The temperature of beaker A was measured at 25°C, and beaker B was 290 K. Select the statement that best describes the two beakers.

A Beaker A has a higher temperature and internal energy than beaker B.
B Beaker B has a higher temperature and internal energy than beaker A.
C Beaker B has a higher temperature than beaker A but there is not enough information to compare internal energies.
D Beaker A has a higher temperature than beaker B but there is not enough information to compare internal energy.

5 4000 joules of energy is required to raise the temperature of 1 kg of paraffin by 2°C. Calculate how much energy is required to raise the temperature of 5 kg of paraffin by 1°C.

A 1 kJ
B 2 kJ
C 10 kJ
D 20 kJ

6 A bucket is filled with equal amounts of hot and cold water. The hot water was originally at 80°C and the cold water at 10°C. The temperature of the final mixture will be approximately:

A 10°C
B 25°C
C 45°C
D 70°C

7 The amount of energy required to melt 3.0 kg of ice at 0.0°C to water at 0.0°C is:

A 1.0×10^6 J
B 3.3×10^5 J
C 1.0×10^5 J
D 3.3×10^6 J

8 A kettle uses 500 kJ of energy when heating the 1.25 L of water inside from 25°C to 90°C. The efficiency of the kettle is:

A 147%
B 53%
C 78%
D 68%

9 Select the statement that best describes the difference between specific heat capacity and specific latent heat.

A Specific heat capacity is the amount of energy it takes to raise one unit of mass 1°C, whereas specific latent heat is the amount of energy it takes to change the state of one unit of mass.
B Specific heat capacity is the amount of energy it takes to raise one unit of mass 1°C, whereas specific latent heat is the amount of energy it takes to change the state of one unit of mass while raising it 1°C.
C Specific heat capacity is the same as specific latent heat.
D Specific heat capacity is the amount of energy it takes to change the state of one unit of mass, and specific latent heat is the amount of energy it takes to increase the temperature of one unit of mass 1°C.

10 A pot of soup is taken off the stove to cool down. It is placed on a cold bench that removes 300 Js^{-1} of heat energy. The soup is stirred, providing 10 Js^{-1} of work to the soup. Assuming there is no heat transfer from the top of the soup, calculate the change in internal energy.

A $-310\,Js^{-1}$
B $-290\,Js^{-1}$
C $290\,Js^{-1}$
D $310\,Js^{-1}$

Short answer

1 Determine whether two objects have the same temperature when the average kinetic energy of the particles in the two objects is identical. Give reasons for you answer.

2 A student attempts to identify a metal by measuring its specific heat capacity. A 90.0 g sample of the metal is heated to 75.0°C and then transferred to a foam cup containing 200 g of water at 20.0°C. The temperature of the final mixture is 25.0°C. Using Table 1 below, determine the metal the student is probably testing.

TABLE 1 Approximate specific heat capacities of some common materials

Material	Specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
lead	130
mercury	140
methylated spirits	250
brass	370
copper	390
iron	440
glass	840
aluminium	900
air	1000
human body	3500
water ice liquid steam	 2100 4200 2000

3 Energy must be supplied to ice to melt it. However, the temperature of the resulting water is no higher than that of the original ice. Explain.

4 Burns caused by steam are much worse than those caused by boiling water. Contrast the amount of energy the body, at a temperature of 37°C, receives from the cooling of 0.10 kg of water from 100°C with that received from the cooling of 0.10 kg of steam originally at 100°C.

5 A 0.50 kg piece of ice at 0°C is mixed with 0.10 kg of steam at 100°C. Determine the final temperature of the mixture.

6 Explain why closing the curtains in the evening helps to keep the inside of a house warm.

7 A 300 g block of copper at a temperature of 120°C is dropped into an insulated thermos filled with 1 L of water at 10°C. Describe the initial energy of the particles in the copper block, compared with those in the water, and how the internal energy of each changes until thermal equilibrium is reached.

8 A tennis player is practising her serve and notices that balls that have been served multiple times are warmer than balls that have been sitting on the court without being hit. Explain why this is the case, detailing the transfer of energy in this system.

9 Explain why, if all objects are at 'room temperature', metal objects feel cooler to touch than wooden objects.

10 Humans have evolved to sweat to avoid overheating. Elephants cannot sweat but are able to increase the blood flow to areas where the skin is thin. Contrast these two different methods of temperature control, explaining how they work.

11 Students have 0.67 kg of an unknown liquid in a calorimeter. They collected the following data:

Energy input (J)	Temperature (°C)
0	−10
20000	2.1
40000	14.3
60000	26.4
80000	38.5
100000	50.7
120000	62.8
140000	74.9

a Create a graph of the results, including an appropriate trend line with equation.

b Interpret the equation of the trend line, include the significance of the intercept and the gradient.

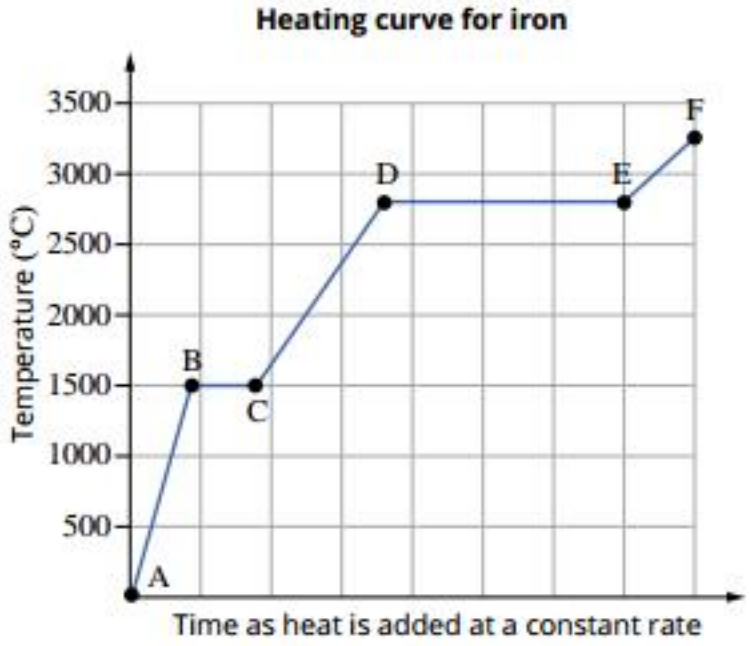
c Using the table below, determine the unknown liquid.

Material	c ($J\,kg^{-1}\,K^{-1}$)	Boiling point (°C)
liquid water	4200	100
glucose solution	1213	–
ethanol	2460	78
methanol	2500	65

12 **a** A student would like to design a model hot air balloon using a candle, a waxed paper bag and string. Describe the energy transformations involved as the balloon rises in the air.

b Describe 'efficiency' and design an experiment that can be used to measure the efficiency of the energy transformation from heat energy to mechanical energy.

13 A block of solid iron is placed in a furnace that maintains a constant heat output. The temperature of the iron is recorded and graphed below.



a Using a diagram, contrast the molecular structure and motion at point A with that at point F.

b Describe the change caused by the addition of heat between points C and D.

c Describe the change caused by the addition of heat between points D and E. Explain how this is different from the change between C and D.

14 A children's toy oven uses a light bulb to bake small cakes in 15 minutes. The bulb operates at 10% efficiency, dissipating the remaining energy as heat. If the bulb operates at 100 J per second, how much energy is used to bake the cakes?

15 Some physical constants for water are shown in the table below.

c_{ice}	$2100\,J\,kg^{-1}\,K^{-1}$
$c_{liquid\ water}$	$4200\,J\,kg^{-1}\,K^{-1}$
c_{steam}	$2000\,J\,kg^{-1}\,K^{-1}$
L_{fusion}	$3.34 \times 10^5\,J\,kg^{-1}$
L_{vapour}	$22.6 \times 10^5\,J\,kg^{-1}$

a Determine how much energy is required to heat a 4.0 kg block of ice at −5.0°C until it boils to form steam at 120°C.

b A freezer removes heat with an efficiency of 60% and runs on 50 J of energy per second. How long (in hours) will it take to cool 400 g of 20°C water to form ice (at 0°C)?

16 With reference to the zeroth law of thermodynamics, explain how a standard laboratory thermometer works.

Topic 2: Ionising radiation and nuclear reactions

Multiple choice

1 Name the force that must be overcome in order to get two hydrogen nuclei close enough to each other for the strong nuclear force to act and subsequently join them to form one nucleus.

A the gravitational force
B the weak nuclear force
C the electromagnetic force
D the force of nature

2 Beta negative radiation is:

A energy emitted from an electron of an atom
B an electron ejected from an atom
C a helium nucleus emitted from an atom
D an electron emitted from the nucleus of an atom

3 Select the type of radiation that is most ionising.

A gamma
B beta
C alpha
D none of the above

4 The value of x in the decay equation ${}^{238}_{92}U \rightarrow {}^{x}_{90}Th + {}^{4}_{2}\alpha + \gamma$ is:

A 238 **B** 236
C 234 **D** 232

5 A radioactive sample of oxygen-15 has a half-life of 110 minutes. If the amount remaining after 5.5 h is 0.80 g, the original sample had a mass of:

A 2.4 g
B 2.8 g
C 6.4 g
D 9.6 g

6 Select the option below that most accurately describes the *nuclear* model of the atom.

A The atom is a spherical region with negative electrons scattered throughout.
B The atom contains a small nucleus surrounded by electrons.
C The atom contains a small nucleus surrounded by electrons in fixed shells.
D The atom contains a small nucleus surrounded by electrons in orbitals.

7 Nuclear fission is:
- **A** the joining together of two or more small nuclei
- **B** splitting a nucleus into two or more pieces
- **C** absorbing a neutron
- **D** undergoing radioactive decay

8 The electron volt (eV) is a unit of measure of:
- **A** mass
- **B** charge
- **C** potential difference
- **D** energy

9 Select the statement that best describes the main hazard of radiation.
- **A** There is damage to living cells due to ionisation.
- **B** The heat produced damages cells.
- **C** Chemical reactions within the body create impurities.
- **D** Radioactive atoms replace other atoms in living organisms.

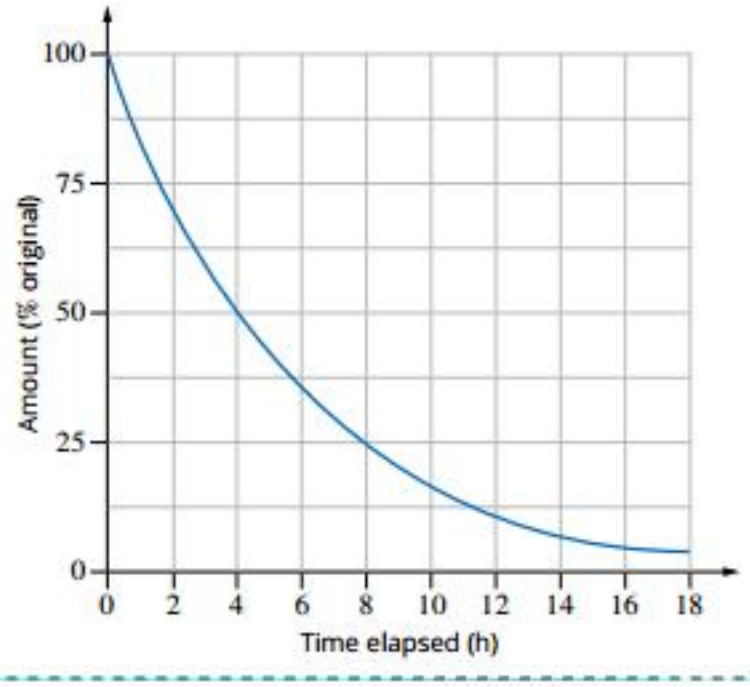
10 A nuclear process occurs in which a neutron collides with an unstable nucleus. The nucleus splits, releasing more neutrons. These neutrons then collide with further unstable nuclei, continuing the process. This is referred to as:
- **A** artificial transmutation
- **B** a chain reaction
- **C** nuclear transmutation
- **D** nuclear fusion

Short answer

1 Complete the following decay equations by replacing Ψ:
- **a** $^{14}_{6}C \rightarrow {}^{14}_{7}N + \Psi$
- **b** $^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi + \Psi$
- **c** $^{60}_{27}Co^{*} \rightarrow {}^{60}_{27}Co + \Psi$
- **d** $^{238}_{92}U \rightarrow {}^{234}_{90}Th + \Psi$

2 Cobalt-60 has a half-life of 5.3 years. A sample of pure cobalt-60 has a mass of 50 μg. Determine the amount of cobalt-60 that remains after:
- **a** 10.6 years
- **b** 15.9 years
- **c** 21.2 years.

3 The radioactive decay of a particular isotope is shown on the graph below. The initial mass of the radioisotope is 20 g.

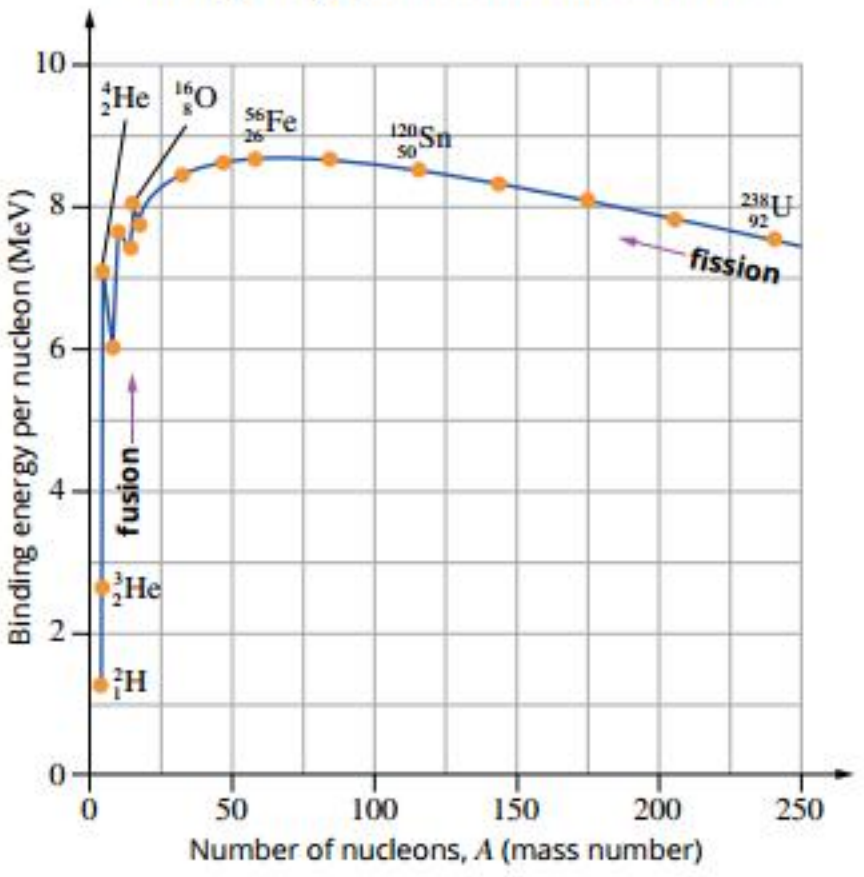


- **a** Determine the time it takes for a 20 g sample to decay to 5.0 g.
- **b** Determine the half-life of the sample.
- **c** Determine how much of the original radioisotope (in grams) remains after 6.0 hours.
- **d** Calculate the amount of the radioisotope remaining (in grams) after 20 hours have elapsed.

4 Describe 'binding energy' and 'mass defect'.

5 Uranium-235 undergoes fission and splits into daughter products of roughly equal mass. Use the graph of binding energy per nucleon to determine how much energy is released per nucleon.

Binding energy per nucleon vs mass number



6 The Sun is currently releasing approximately 3.9×10^{26} W from nuclear fusion reactions. Calculate the mass loss this equates to each day.

7 Lead-210 undergoes beta negative decay twice and then undergoes alpha decay, each time forming a new substance.
- **a** Write a series of equations that describe this decay chain, identifying the daughter nuclides.
- **b** Explain why the polonium isotope in this decay chain would be dangerous to ingest but is relatively safe to observe from close proximity.

8 Carbon-14 has a half-life of 5730 years. Describe 'half-life' and explain how it can be used to estimate the age of organic materials.

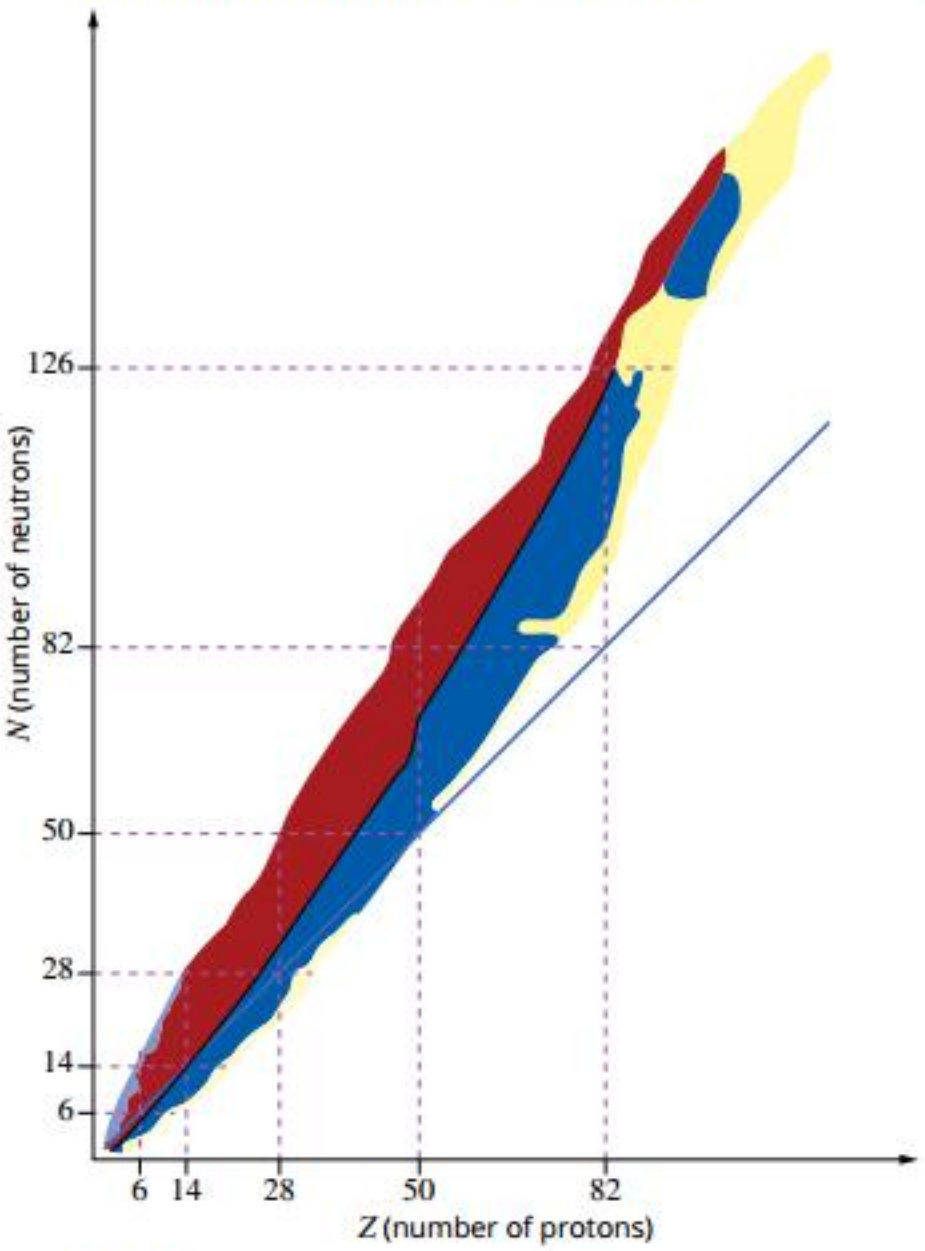
9 As a doctor you prescribe a course of radiotherapy for a patient with breast cancer. The procedure involves inserting a radioactive source into the affected region. Explain which type of radiation source—alpha, beta negative or gamma—you would prefer to use and why.

10 Consider the fission reaction below:

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + \_\_\_\_ + 170\,MeV$$

- **a** Determine the identity of the missing item.
- **b** Convert the energy released into joules.
- **c** Determine how many of these reactions are needed each second to generate 3.0 GW of power.
- **d** The rest mass of a proton and neutron are almost equal at 1.67×10^{-27} kg. Calculate the mass of U-235 that is needed each second to generate 3.0 GW.

11 The figure below shows the number of protons for different isotopes. Each isotope is colour-coded with the type of radioactive decay that is most often observed. Stable nucleotides are represented in black.



- **a** Explain how the forces that act within the nucleus of a stable atom provide stability. Identify the type of nucleon each force acts between.
- **b** In the previous figure, the red nuclei have more neutrons within them than the stable isotope of the same element. Describe the forces acting within these nuclei and contrast these with the forces acting in the stable nuclei.
- **c** Predict the type of decay the red nuclei would most commonly experience, detailing how this decay leads to a more stable nucleus.
- **d** Both the yellow- and blue-coloured nuclei have fewer neutrons than the stable isotopes. Describe the type of decay each would undergo and explain how this decay creates a more stable nucleus for these nucleotides.

12 Uranium-235 has a half-life of approximately 703.8 million years and decays to thorium-231, releasing energy in the process. Alternatively, uranium-235 can be bombarded with a neutron and fission into smaller nuclei, releasing energy.

- **a** Describe 'artificial transmutation' and contrast it with natural radioactive decay.
- **b** Uranium-235 can fission into different products. One option is given below.

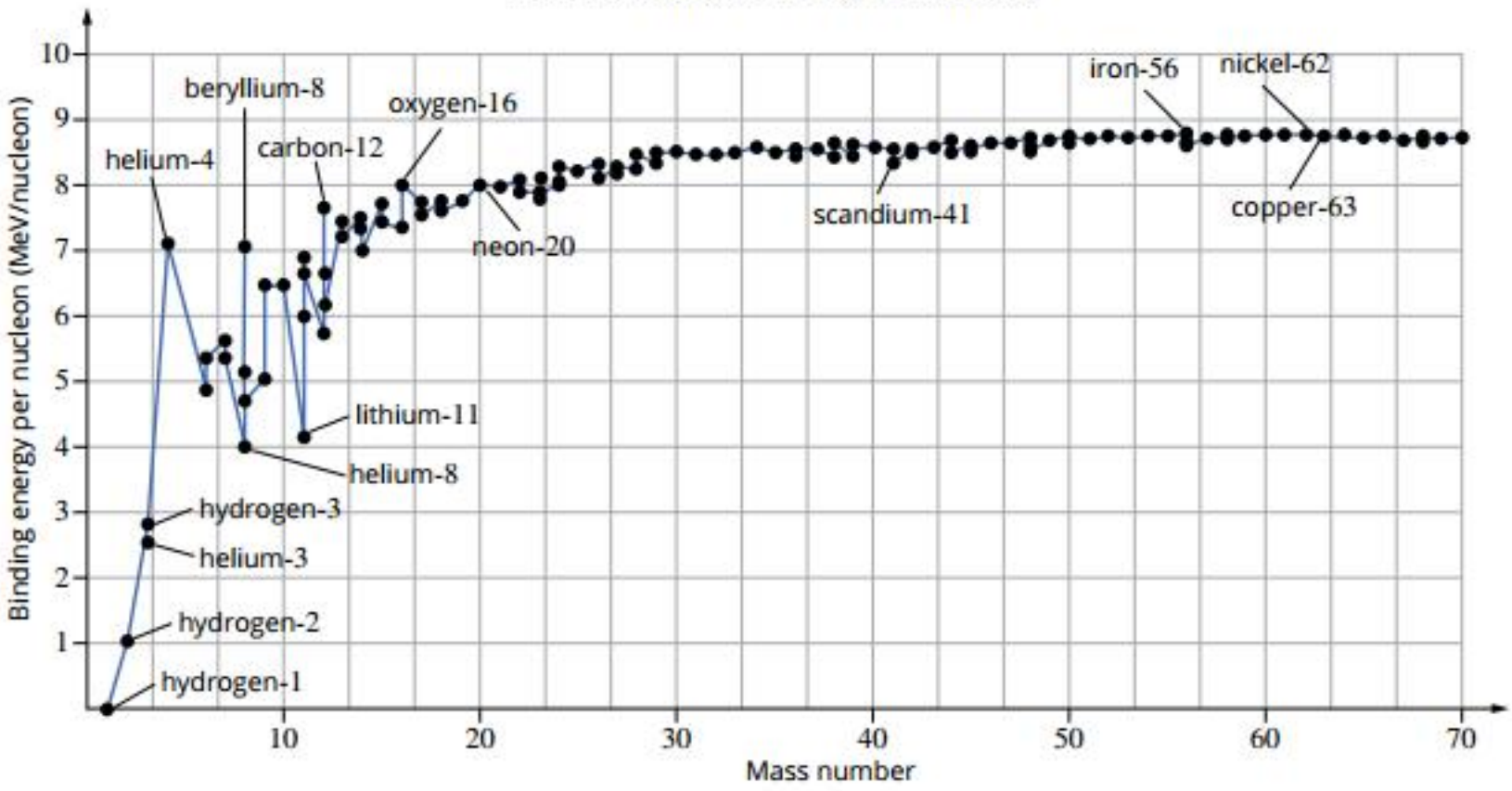
$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{131}_{53}I + {}^{102}_{39}Y + x\,{}^{1}_{0}n$$

Calculate the number of neutrons produced in this reaction.

- **c** Describe fission chain reactions, using the uranium-235 fission reaction as an example, and the role of control rods and moderators in nuclear reactors.
- **d** Iodine-131, a daughter nuclide of this fission reaction, is radioactive, with a half-life of approximately 8 days. It is often used in medical procedures, including the treatment of cancer. Using your understanding of nuclear waste, determine if the iodine produced could be used for medical treatment. Explain your reasoning.
- **e** Find the energy released during one fission reaction. The required data are:
  Mass of neutron = 1.008 665 u
  Mass of uranium-235 = 235.043 929 9 u
  Mass of iodine-131 = 130.906 124 6 u
  Mass of yttrium-102 = 101.933 56 u

13 The graph below shows the binding energy per nucleon up to mass number 70.

Binding energy per nucleon for selected isotopes from mass number 1 to mass number 70



a Using the information from the graph, determine the energy release for the fusion of hydrogen-2 (deuterium) with hydrogen-3 (tritium) to form helium-4.

b Using the information from the graph of binding energy per nucleon above, describe the process that nuclei below nickel undergo in order to become more stable.

c Describe the conditions required for the process in part b to take place, and why they are necessary.

d Contrast this process with the process that heavy elements undergo to release energy and become more stable.

14 Carbon dating uses the ratio of carbon-12 to carbon-14 in a specimen to determine its age. All living organisms have a carbon-12 to carbon-14 ratio of $1 : 1.3 \times 10^{-12}$, which begins to decrease upon death. A bone fragment contains 200.0g of carbon where the ratio of carbon-12 to carbon-14 is $1 : 4.17 \times 10^{-13}$. If the half-life of carbon-14 is 5730 years, determine the age of the bone.

15 The nuclide ${}^{188}_{7}\text{Ir}$ (isotopic mass = 187.958853 u) undergoes beta positive decay with an energy of 1.78 MeV. Use this information to determine the mass of the daughter nuclide in atomic mass units.

16 The Trinity bomb test in 1945 was the world's first successful detonation of a fission nuclear weapon. It used uranium-235 and released the equivalent of 25 kilotons of trinitrotoluene (TNT). If 1 ton of TNT produces 5×10^{9} J of energy, determine the amount of uranium-235 used in the Trinity test.

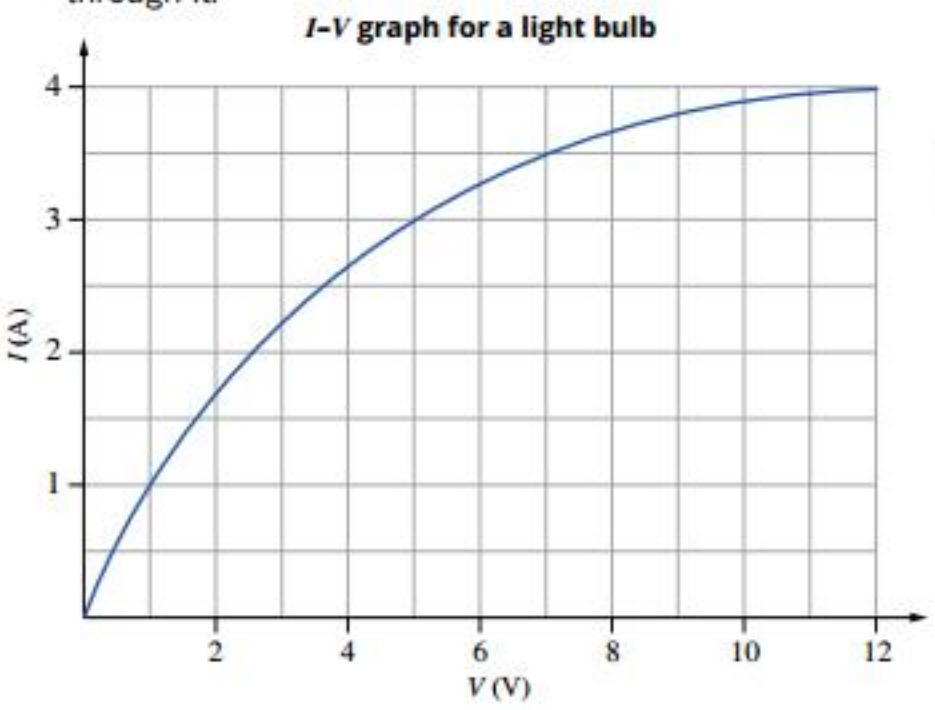
Topic 3: Electrical circuits

Multiple choice

1 Electricity passing through a copper wire primarily relates to the movement of:

A protons
B neutrons
C electrons
D atoms

2 The *I–V* graph for a light bulb is shown. Determine the resistance of the bulb when a 4.0A current is passing through it.



A 3.0W
B 3.0Ω
C 0.33Ω
D 0.33W

3 A circuit is made from a battery and four light bulbs. The battery will go flat quickest when:

A all the lights are wired in series
B some of the lights are wired in series and some in parallel
C all the lights are wired in parallel
D It cannot be determined unless the resistance of the light bulbs is known

4 Determine which of these statements is correct for a series circuit.

A The supply voltage divides among the components and the current is constant everywhere around the circuit.
B The current divides among the components and the supply voltage is constant everywhere around the circuit.
C The power dissipated by all components is equal regardless of their resistance.
D The power dissipated by all components depends on the differing current through each.

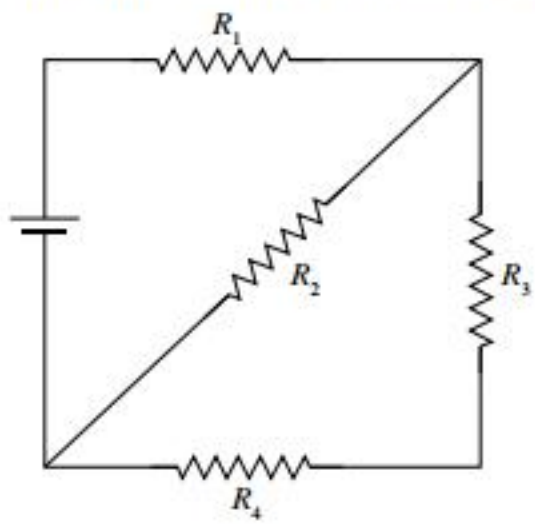
5 The potential difference between the two terminals on a battery is 12.0V. Calculate the amount of work required to transfer 8.0C of charge across the terminals.

A 1.5J
B 96J
C 0.66J
D 12.0J

6 A wire in a circuit separates into two wires at a junction. If the current in the original wire is 12A, which of the following is a possible combination of currents for the two wires leaving the junction?

A 10A and 10A
B 12A and 12A
C 3A and 4A
D 8A and 4A

7 In the following circuit, resistor 2 and resistor 3 are:



A in series
B in parallel
C opposite
D in order

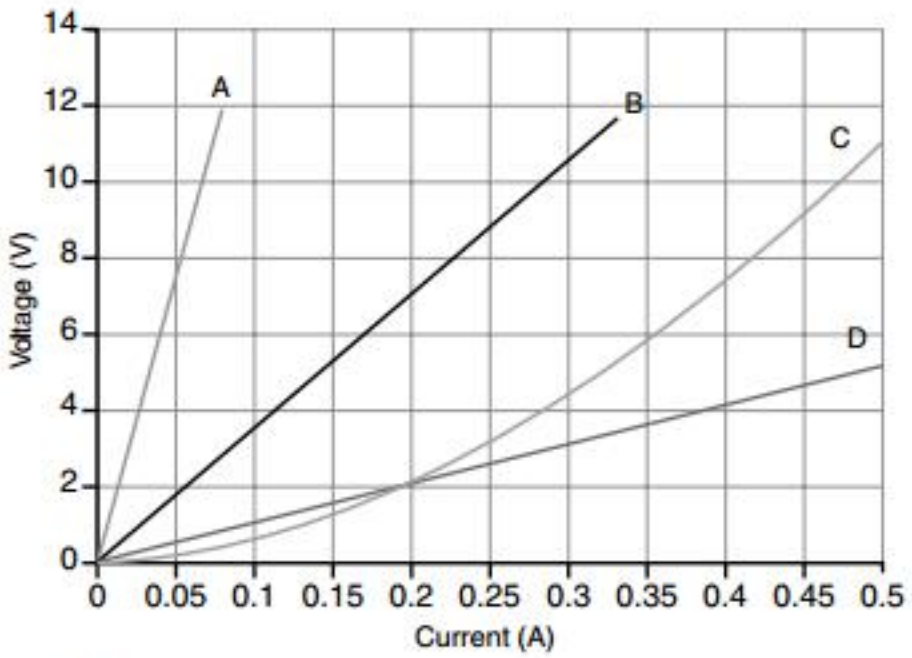
8 A heating radiator is connected to a 240V power supply. The heater dissipates 2.4MJ of energy in 20min. Calculate the power dissipated by the heating element.

A 0.5W
B 2W
C 500W
D 2000W

9 The total energy output from loads within a circuit must be equal to:

A the equivalent resistance of the circuit
B the energy inputs to the circuit
C the usable work generated by the circuit
D the potential difference of the circuit

10 The voltage–current characteristics were measured for four different resistors. Identify the resistor with the highest resistance.



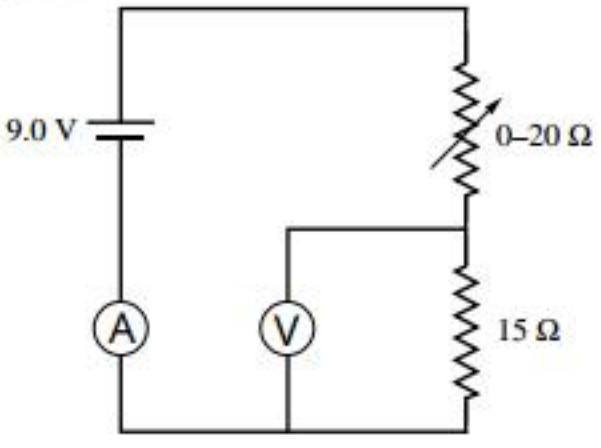
A A
B B
C C
D D

Short answer

1 A negatively charged balloon and some positively charged confetti in a container are brought together so they are close but do not touch. Explain what will happen.

2 Sketch the shape of the *I–V* graph for an ohmic resistor and a non-ohmic resistor on the same axis (no numbers are needed).

3 A variable resistor and a fixed resistor are wired to a supply as shown.

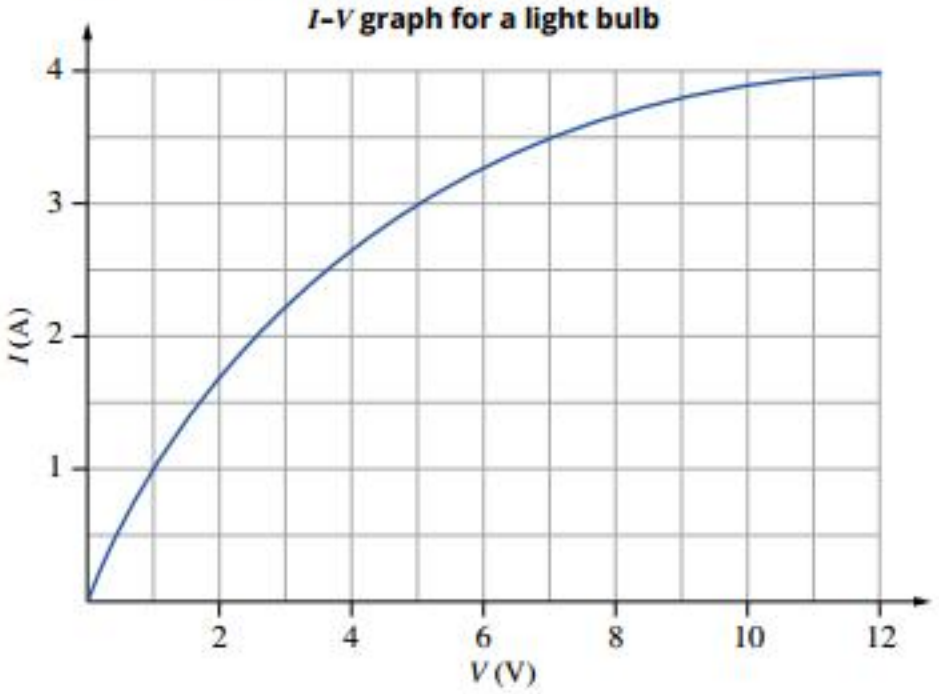


a Determine the possible range of readings on the ammeter.
b Determine the possible range of readings on the voltmeter.

4 A kettle rated at 2.0 kW is plugged into the mains supply (230 V).
a Determine how much current flows when the kettle is in operation.
b Calculate how many joules of energy the kettle uses if it takes 3.0 minutes for it to boil some water.
c Determine how many coulombs of charge flow in the 3.0 minutes.
d Determine how many electrons flow in the 3.0 minutes.

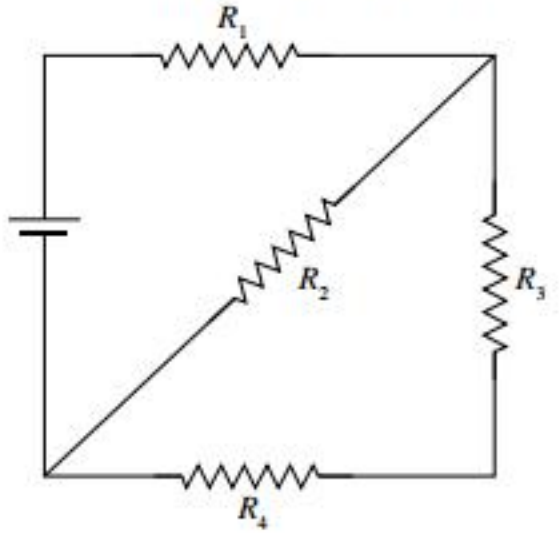
5 A light bulb with the *I–V* characteristics shown below is connected to a 9 V battery. Calculate the power dissipated in the bulb.

***I–V* graph for a light bulb**



6 Describe the following terms, include the unit of measurement.
a electric current
b electrical potential difference
c power dissipation over resistors

7 Four identical 200 Ω resistors and a 12 V power supply are arranged as shown in the circuit. Calculate the current through R_3, and the power dissipated by R_2.



8 An unknown ohmic component was placed into a simple circuit and the voltage drop and current through the resistor were measured. Determine the resistance of the unknown component.

Voltage (V)	Current (mA)
2	19
4	43
6	62
8	78
10	101

9 Draw a circuit diagram, using standard symbols that would allow the resistance of an unknown fixed resistor to be determined.

10 In a science demonstration, a student rubs a balloon on their hair. As they slowly raise the balloon, their hair appears to be lifted towards the balloon. Explain why this occurs.

11 Christmas-tree lights consist of a string of bulbs that can be wired in either series or parallel.

a State whether it is better to arrange the bulbs in series or parallel. Justify your answer.

b Describe what would happen to the total resistance if the bulbs were wired in parallel and additional bulbs were added.

c Each bulb is rated at 3V, 6W. A 13A fuse is placed immediately after the 3V power supply. Calculate the maximum number of bulbs in parallel that can be used so that the fuse does not melt.

d Describe what would happen to the total resistance if the bulbs were wired in series.

e Predict what would happen to the fuse and to the brightness of the lights if a series combination of bulbs was wired to the same 3V supply in conjunction with the 13A fuse. Justify your answer.

12 A piece of copper wire and a piece of plastic are placed across two terminals side by side, and a current is passed through them.

a It is noticed that the wire gets hot if the current is left on for any length of time, but the plastic does not. Explain why this is so.

b Using the wire and plastic as an example, describe 'electrical resistance'.

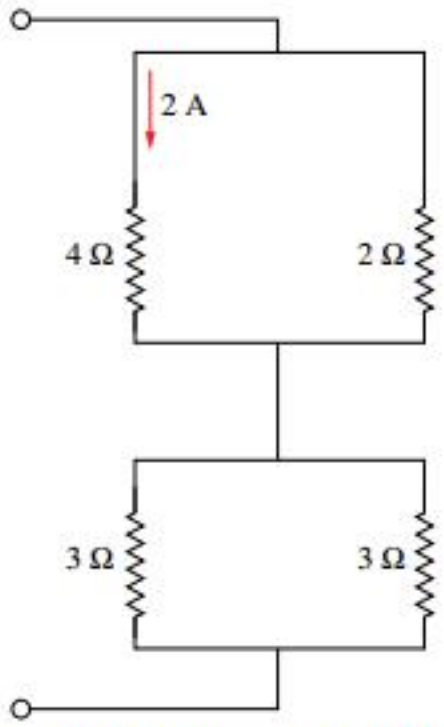
c Design a method that could be used to determine the resistance of the copper wire. Include safe working practices.

d Another experiment obtained the following results to predict the current that will be used when 24V is applied across the copper wire.

Voltage (V)	Current (A)
0.5	8
1.0	10
1.5	25

Give two pieces of advice that could improve these results.

13 A circuit is created using a 4Ω resistor, two 3Ω resistors and a 2Ω resistor, as shown below. When connected to a power supply, 2A of current flows through the 4Ω resistor.



a Calculate the total current that is supplied to the circuit.

b Calculate the equivalent resistance of this circuit.

c Calculate the voltage supplied to the circuit.

d With the same resistors and power supply, design a circuit that has the minimum current in the circuit going through the 2Ω resistor.

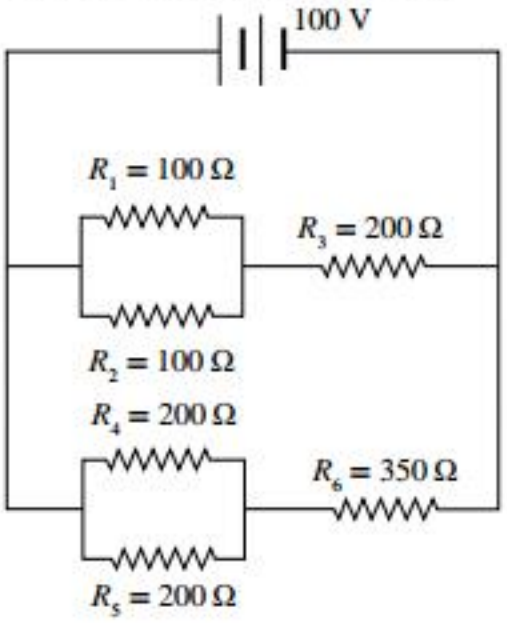
14 An experiment is conducted to measure the resistance of an ohmic conductor. The conductor is connected to a variable power source and the current is measured for different voltages.

The following data is collected:

Voltage (V)	Current (mA)
0.1	1.54
0.2	3.08
0.3	4.62
0.4	6.15

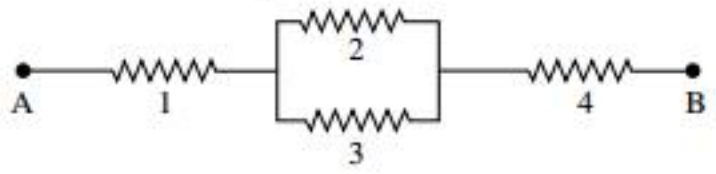
a Graph the results.
b From the graph, calculate the resistance of the conductor.

15 Consider the following circuit.

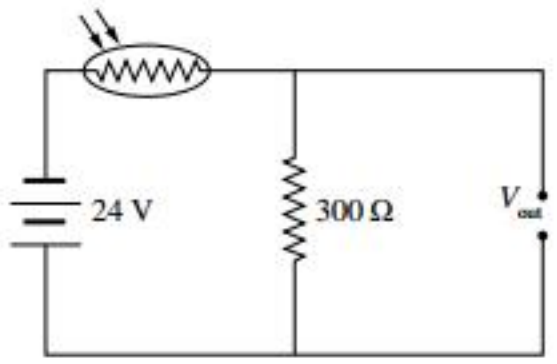


Calculate the:
a equivalent resistance of the circuit
b current in the circuit
c current across each resistor
d power dissipated across each resistor
e total power of the circuit.

16 Four 150Ω resistors are connected as shown. The maximum power that can be dissipated safely in any one resistor is 2W. Determine the maximum power that can be dissipated in this circuit.



17 A light-dependent resistor (LDR) changes its resistance based on the intensity of light it receives. Typically, it has high resistance in low light, and its resistance decreases as the light increases. A circuit in a smart device uses an LDR to turn on the device when the ambient light is above a certain level. Accordingly, the smart device turns on when the output voltage, V_{out}, passes a specific threshold and the resistance of the LDR is 150.0Ω.



a Calculate the value of V_{out} at which the smart device should activate.
b Determine what would you expect V_{out} to become when it is very dark.

18 The water model and the bicycle chain analogies used for electric circuits are helpful in understanding the fundamental concepts of electricity (see pages 129–130). Design your own analogy for an electric circuit or a component of an electric circuit.

19 An experiment is conducted to investigate the resistance of a non-ohmic conductor under different conditions. Consider various techniques that could be used to test the resistance of the conductor.

UNIT 2 Linear motion and waves

TOPIC 1 Linear motion and force

TOPIC 2 Waves

Unit 2 objectives

Students will:

- describe ideas and findings about linear motion and force, and waves
- apply understanding of linear motion and force, and waves
- analyse data about linear motion and force, and waves
- interpret evidence about linear motion and force, and waves
- evaluate processes, claims and conclusions about linear motion and force, and waves
- investigate phenomena associated with linear motion and force, and waves.

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CHAPTER

06 Vectors and linear motion

Motion is a fundamental aspect of everyday life. In this chapter, you will learn how to use the mathematical quantities of scalars and vectors to understand the concepts of motion. Basic terms used to describe motion—such as distance and speed—will be combined with direction to provide a more comprehensive view. By using displacement, velocity and acceleration, you can more accurately model how objects move in the world around you. From a train pulling into a station to a swimmer completing a lap of a pool, physics can model the motion of almost anything, from simple to complex.

Syllabus subject matter

Linear motion

- Contrast vectors and scalars, and use these terms to categorise physical quantities, such as velocity and speed. **6.1**
- Symbolise vectors graphically and algebraically, such as **F**, $\bar{F}$, $\vec{F}$ or F. **6.1**
- Calculate resultant vectors through the addition and subtraction of two vectors in one dimension. **6.1**
- Describe the concepts of displacement, velocity and acceleration. **6.2, 6.3, 6.4**
- Compare instantaneous and average velocity. **6.3**
- Interpret linear motion graphs to describe the motion of an object, referring to the
  - intercepts, gradients and uncertainties (using minimum and maximum lines of best fit) of displacement–time and velocity–time graphs. **6.6**
  - areas under velocity–time and acceleration–time graphs using simple geometry. **6.6**
- Solve problems relating to uniformly accelerated motion in one dimension using $v = u + at$, $s = ut + \frac{1}{2}at^2$ and $v^2 = u^2 + 2as$. **6.5**
- Interpret experimental data to determine the value of acceleration due to gravity on the Earth's surface. **6.6**

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6.1 Vectors

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the concepts of scalars and vectors, and the difference between them
- write vectors using appropriate notation and sign conventions
- draw diagrams of vectors
- add and subtract resultant vectors in one dimension using graphical and algebraic methods.

You will encounter many physical quantities in the world. For example, time, mass and distance are all physical quantities. These quantities are measured in the units seconds, kilograms and metres respectively.

Some measurements only make sense when a direction is included. For example, a global positioning system (GPS) tells you when to turn and in which direction. Without both instructions, the information is incomplete. All physical quantities can be divided into two broad groups—scalars and vectors—based on what information is required for the quantity to make sense.

SCALARS

Scalar measurements only require a magnitude. Several properties in nature can be measured or described using only a number and unit. For example, if you were to measure the time taken for a student to travel to school, you would need the **magnitude** (size) and the **units** to understand the journey. You could say it takes 60 minutes or 1 hour, as long as you give a number and a unit. Quantities that require magnitude and units are called scalar quantities. Scalars do not need direction. Examples of scalar quantities are:

- time
- distance
- volume
- speed.

VECTORS

Unlike scalars, **vector** measurements require magnitude, units and direction to make sense. Quantities that require magnitude, units and direction are called vector quantities. Examples of vector quantities are:

- position
- displacement
- velocity
- acceleration
- force.

These measures are discussed in more detail in the coming chapters.

Several different types of vector notation are used in books and journals. For example, force can be written as $\mathbf{F}$, $\bar{F}$, $\vec{F}$ or F, while velocity can be written as $\mathbf{v}$, $\bar{v}$, $\vec{v}$ or v.

This book uses italics to represent vectors; for example, force is written as *F* and velocity as *v*.

Scalars are represented by symbols in italics, such as *t* for time and *d* for distance. Vectors are often represented in the same way—it is usually clear from the context whether a scalar or vector is meant.

Vectors as arrows

Scalar measurements only require magnitude. Vector measurements require magnitude *and* direction. A vector can be visually represented as an arrow. Figure 6.1.1 shows two vector diagrams. In a **vector diagram**, the length of the arrow indicates the magnitude of the vector. The arrowhead shows the direction of the vector, which is always from its tail to its head.

Recall that a force is a push or a pull and the unit of measure for force is the **newton** (N). If you push a book to the right, it will respond differently from the way it will respond if you push the book to the left. Therefore, a force is only described properly if a direction is included, and so force is a vector. Force is an important concept to understand in physics, so many of the examples in this chapter refer to forces.

In some vector diagrams, the length of the arrow is drawn to scale so that it accurately represents the magnitude of the vector.

In the scaled vector diagram in Figure 6.1.2, a force $F = 4\,\text{N}$ left acting on the toy car is drawn as a 2 cm arrow. In this example a scale of 1 cm = 2 N force is used.

An exact scale for magnitude is not always used. However, it is important that vectors are drawn relative to one another. For example, a vector of 50 m north should be about half as long as a vector of 100 m north.

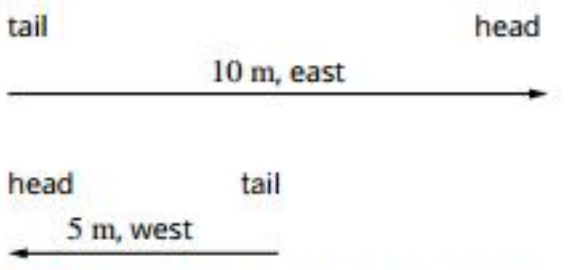


FIGURE 6.1.1 Two vector diagrams. The top vector is twice as long as the bottom vector, so it represents a measure twice the magnitude of the bottom vector. The arrowheads indicate that the vectors are in opposite directions.

FIGURE 6.1.2 A force of 4 N to the left acts on a toy car.

Point of application of arrows

Vector diagrams may be drawn differently, depending on what they are depicting. Throughout this book, vectors are drawn using the following conventions:

- Force vectors have the tail end of the arrow drawn at the point where the force is applied to the object.
- Force due to gravity vectors have the tail end of the arrow drawn at the centre of mass of the object.
- Displacement vectors have the tail of the arrow at the starting position of the object.
- Friction vectors are drawn parallel to the surface and in the opposite direction of motion.

Figure 6.1.3 shows a force applied by a foot to a ball (95 N east) and an opposing friction force (20 N west).

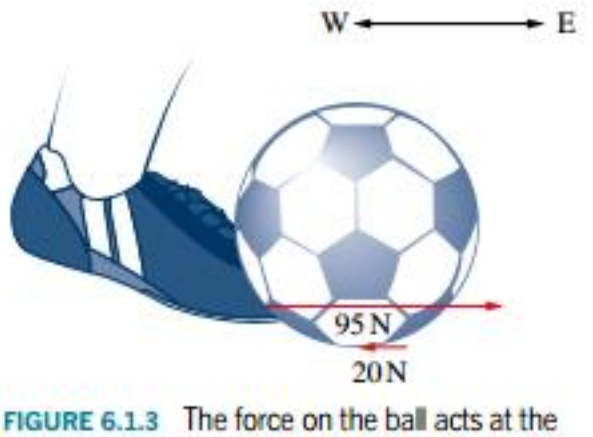


FIGURE 6.1.3 The force on the ball acts at the point of contact between the ball and the foot. The friction force acts between the ball and the ground. The kicking force, as indicated by the length of the arrow, is larger than the friction force.

VECTORS IN ONE DIMENSION

Vectors need a direction to make sense. However, for any description of a vector quantity to be useful, the direction should be described using a convention that everyone understands. For vector problems in one **dimension**, several **direction conventions** can be used. For example:

- forwards or backwards
- up or down
- left or right
- north or south
- east or west.

As you can see, for vectors in one dimension there are only two directions possible. The two directions must be in the same dimension or along the same line. The direction convention used should be presented graphically in all vector problems. This is shown in Figure 6.1.4. Arrows like these are placed near the vector diagram so it is clear which convention is being used.

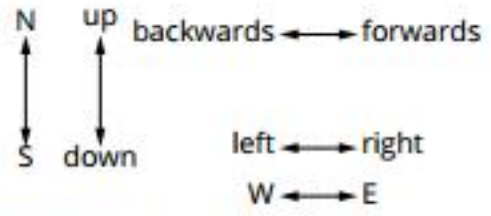


FIGURE 6.1.4 Some common one-dimensional direction conventions

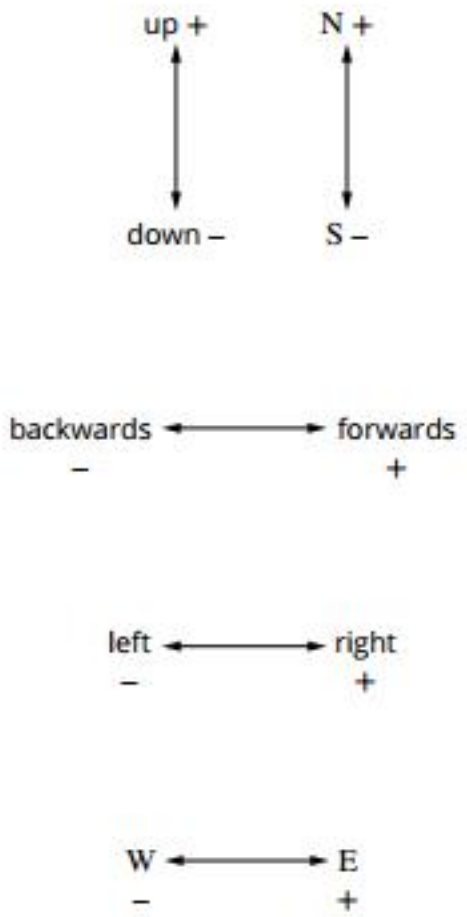


FIGURE 6.1.5 One-dimensional direction conventions can also be expressed as sign conventions.

Sign conventions

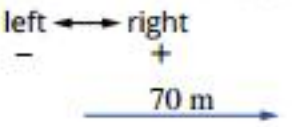
In calculations involving one-dimensional vectors, a sign convention can be used to represent physical directions as positive and negative values. For example, forwards can be positive and backwards can be negative, or right can be positive and left can be negative. A vector of 100 m up can be described as +100 m. The relationship between sign and direction conventions must be clearly indicated in a legend or key. Some examples are provided in Figure 6.1.5.

The advantage of using a sign convention is that the signs of positive and negative can be entered into a calculator, but the words 'up' and 'right' cannot. This will be useful when adding vectors together.

Worked example 6.1.1

DESCRIBING VECTORS IN ONE DIMENSION

A student travels 70 m right, as shown in the vector below.



a Describe the distance travelled by the student, using a scalar quantity.

Thinking	Working
Determine what information is required to describe the distance.	As distance is a scalar quantity, it requires a magnitude and units to describe it.
Describe the distance travelled using a magnitude and units.	The distance is 70 m.

b Describe the displacement of the student, using a vector quantity.

Thinking	Working
Determine what information is required to measure the displacement.	As displacement is a vector quantity, the measurement requires a magnitude, units and direction.
Identify the direction convention used in the vector diagram.	The vector is pointing to the right according to the direction convention.
Note the magnitude, unit and direction of the displacement.	The displacement is 70 m to the right.

c Describe the displacement of the student using an appropriate sign convention.

Thinking	Working
Convert the physical direction to the corresponding mathematical sign. The direction of right is positive, and the direction of left is negative.	The arrow is pointing right, so the sign is +.
Represent the displacement with a mathematical sign, magnitude and unit.	The displacement is +70 m.

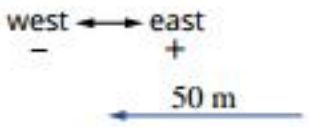
d Contrast the scalar and vector measurements.

Thinking	Working
Contrast the measurements by identifying differences.	The scalar measurement does not have direction, whereas the vector measurement has a direction (70 m right). It can also be written using a sign convention (+70 m).

➤ Try yourself 6.1.1

DESCRIBING VECTORS IN ONE DIMENSION

A ball travels 50 m west as shown in the vector below.



a Describe the distance travelled by the ball as a scalar quantity.

b Describe the displacement of the ball using a vector quantity.

c Describe the displacement of the ball using an appropriate sign convention.

d Contrast the scalar and vector measurements.

ADDING VECTORS IN ONE DIMENSION

More than one vector may act on an object. If this is the case, it is helpful to analyse the associated vector diagrams to find out the overall or combined effect of the vectors. When two or more vectors are in the same dimension, it means that the vectors are either pointing in the same direction or in the opposite direction. They are **collinear** (in line with each other). For example, the vector measurements 10 m west, 15 m east and 25 m west are all in one dimension. They are all in the same or opposite direction to each other. When vectors are combined, it is called adding vectors.

Graphical method of adding vectors

Vector diagrams, as shown in Figure 6.1.6, are convenient for adding vectors. To combine vectors in one dimension, draw the first vector, and then start the second vector with its tail at the head of the first vector. Continue adding arrows 'head to tail' until the last vector is drawn. The sum of the vectors, or the **resultant** vector, is drawn from the tail of the first vector to the head of the last vector.

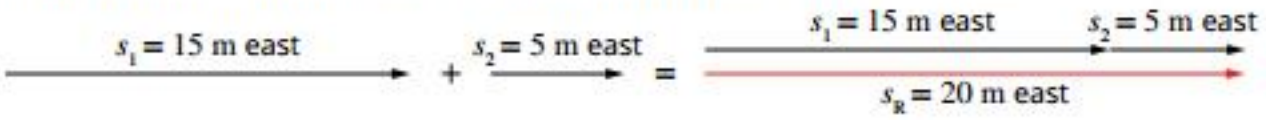


FIGURE 6.1.6 Adding vectors head to tail. This diagram represents the addition of 15 m east and 5 m east. The resultant vector, shown in red, is 20 m east.

In Figure 6.1.6, the two vectors s_1 (15 m east) and s_2 (5 m east) are drawn separately. The two vectors are then drawn with s_1 and s_2 connected head to tail. The resultant vector s_R is drawn from the tail of s_1 to the head of s_2. The magnitude (size) of the resultant vector can be deduced from the magnitudes of the separate vectors: 15 m + 5 m = 20 m.

Alternatively, vectors can be drawn to scale such as 1 m = 1 cm. The resultant vector is then directly measured from the scale diagram. The direction of the resultant vector is the same as the direction from the tail of the first vector to the head of the last vector.

Algebraic method of adding vectors

To add vectors in one dimension algebraically, a sign convention is used to represent the direction of the vectors, as shown in Figure 6.1.5. When applying a sign convention, it is important to provide a key explaining the convention used.

The sign convention allows you to enter the signs and magnitudes of vectors into a calculator. The sign of the final magnitude gives the direction of the resultant vector.

Worked example 6.1.2

ADDING VECTORS IN ONE DIMENSION USING ALGEBRA

Use the sign and direction conventions shown in Figure 6.1.5 to determine the resultant vector of a student who walks 25 m west, 16 m east, 44 m west and then 12 m east.	
Thinking	**Working**
Apply the sign conventions to change each of the directions to signs.	25 m west = –25 m 16 m east = +16 m 44 m west = –44 m 12 m east = +12 m
Add the magnitudes and their signs together.	Resultant vector = (–25) + (+16) + (–44) + (+12) = –41 m
Refer to the sign and direction conventions to determine the direction of the resultant vector.	Negative is west. Therefore, the resultant vector = 41 m west.

➤ Try yourself 6.1.2

ADDING VECTORS IN ONE DIMENSION USING ALGEBRA

Use the sign and direction conventions shown in Figure 6.1.5 to determine the resultant vector of a box that has the following forces acting on it: 16 N up, 22 N down, 4 N up and 17 N down.

SUBTRACTING VECTORS IN ONE DIMENSION

In physics there are times when the difference between two vectors must be determined. For example, to find a change in velocity you subtract the initial velocity from the final velocity. One way to subtract one vector from another is to add the opposite vector.

To find the difference between two vectors, you must subtract the initial vector from the final vector. To do this, work out which is the initial vector, then reverse its direction. These two vectors are then added: the final vector and the opposite of the initial vector.

This technique can be applied both graphically and algebraically.

Double negatives

When a negative number is multiplied by another negative number, the result is a positive number. It is also illustrated when a negative number is subtracted from another number. The effect is to add the two numbers together. For example: (5) – (–2) = 7.

It is important to differentiate between the terms 'subtract', 'minus', 'take away' or 'difference between' and the term 'negative'. The terms 'subtract', 'minus', 'take away' and 'difference between' are processes, such as add, multiply and divide. They are grouped together on your calculator. The term 'negative' is a property of a number that means that it is the opposite of positive. There is a separate button on your calculator for this property.

Graphical method of subtracting vectors

Velocity is a quantity that gives an indication of how fast an object is moving. It is a vector because the direction is important when stating the velocity of an object. For example, the velocity of the tennis ball moving towards the racquet in Figure 6.1.7 is different from the velocity of the tennis ball as it leaves the racquet. The concept of velocity is covered in more detail in Module 6.2, but it is useful to use the example of velocity now when discussing the subtraction of vectors. The processes applied to the subtraction of velocity vectors works for all other vectors.

FIGURE 6.1.7 As velocity is a vector, direction is important. The tennis ball has a different velocity when it leaves the racquet from when it travelled towards the racquet.

To subtract velocity vectors in one dimension using a graphical method, determine which vector is the initial velocity and which is the final velocity. The final velocity is drawn first. The initial velocity is then drawn, but in the opposite direction to its original form. The sum of these vectors, or the resultant vector, is drawn from the tail of the final velocity to the head of the reversed initial velocity. This resultant vector is the difference between the two velocities, or Δv.

In Figure 6.1.8, the two velocity vectors, v_1 ($9\,m\,s^{-1}$ east) and v_2 ($3\,m\,s^{-1}$ east) are drawn separately. The vectors have the same direction (east). To find the difference between the vectors, subtract the initial velocity from the final velocity. To do this, draw v_2. Then draw v_1 below v_2 in the opposite direction, $-v_1$ ($9\,m\,s^{-1}$ west), with the tail of $-v_1$ in line with the head of v_2 as shown in Fig. 6.1.9. The resultant vector, Δv, is drawn from the tail of v_2 to the head of $-v_1$. In Figure 6.1.9 the resultant vector is shown in red. The resultant vector is $6\,m\,s^{-1}$ west.

$$\Delta v = (+3) + (-9) = -6\,m\,s^{-1}$$

Alternatively, you could draw the vectors to scale and then measure the resultant vector against that scale, for example $1\,m\,s^{-1} = 1\,cm$.

The symbol Δ (delta) is used to describe the change in some variable. For example, Δv means the change in velocity.

To find the difference between two vectors, or a change in vectors, subtract the initial vector from the final vector. Vectors are subtracted by adding the negative of a vector.

FIGURE 6.1.8 For vectors, $v_2 - v_1$ involves adding the opposite direction of v_1; $-v_1$ as shown.

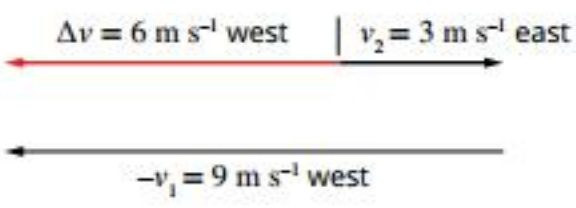


FIGURE 6.1.9 The resultant of $v_2 + (-v_1)$ is given by Δv in red.

Algebraic method of subtracting vectors

To subtract velocity vectors in one dimension algebraically, a sign convention is used to represent the direction of the velocities. Some examples of one–dimensional directions include east and west, north and south and up and down. These options are replaced by positive (+) or negative (–) signs when calculations are performed. To change the direction of the initial velocity, simply change the sign from positive to negative or from negative to positive. The equation for finding the change in velocity is:

change in velocity = final velocity – initial velocity

$$\Delta v = v_2 - v_1$$

change in velocity = final velocity + the opposite of the initial velocity

$$\Delta v = v_2 + (-v_1)$$

The final velocity is added to the opposite of the initial velocity. The change in velocity is a vector, so it will consist of a sign and a magnitude. The sign of the answer can be compared with the sign and direction convention (Figure 6.1.5, page 202) to determine the direction of the change in velocity.

Worked example 6.1.3

SUBTRACTING VECTORS IN ONE DIMENSION USING ALGEBRA

Determine the change in velocity of an aeroplane as it changes from 255 m s^{-1} west to 160 m s^{-1} east. Use the sign and direction conventions shown in Figure 6.1.5 on page 202.

Thinking	Working
Apply the sign and direction conventions to change the directions to signs.	$v_1 = 255\,m\,s^{-1}$ west $= -255\,m\,s^{-1}$ $v_2 = 160\,m\,s^{-1}$ east $= +160\,m\,s^{-1}$
Reverse the direction of the initial velocity, v_1, by reversing the sign.	$-v_1 = 255\,m\,s^{-1}$ east $= +255\,m\,s^{-1}$
Use the formula for change in velocity to calculate the magnitude and the sign of Δv.	$\Delta v = v_2 + (-v_1)$ $= (+160) + (+255)$ $= +415\,m\,s^{-1}$
Refer to the sign and direction conventions to determine the direction of the change in velocity. Positive is east.	$\Delta v = 415\,m\,s^{-1}$ east

➤ Try yourself 6.1.3

SUBTRACTING VECTORS IN ONE DIMENSION USING ALGEBRA

Determine the change in velocity of a rocket as it changes from 212.0 m s^{-1} up to 2200.0 m s^{-1} up, using the sign and direction conventions shown in Figure 6.1.5 on page 202.

6.1 Review

SUMMARY

- Scalar quantities can be measured or described using just a magnitude.
- Vector quantities have a magnitude and a direction. They are written using vector notation, such as $\mathbf{F}$, $\tilde{F}$, $\vec{F}$ or F.
- Combining vectors is known as adding vectors.
- Adding vectors in one dimension can be done graphically by using vector diagrams. After adding vectors head to tail, the resultant vector can be drawn from the tail of the first vector to the head of the last vector.
- Adding vectors in one dimension can be done algebraically by applying a sign convention. Vectors with direction become vectors with either positive or negative signs.
- To find the difference between, or change in vectors, subtract the initial vector from the final vector.
- Vectors are subtracted by adding the negative, or opposite, of a vector.
- Vector subtraction can be determined graphically using a scale.
- Vector subtraction in one dimension can be determined algebraically.

KEY QUESTIONS

Describe

1 Recall what property is required for both scalar and vector quantities.

2 Identify the property that is used when measuring vector quantities, but is not used when measuring scalar quantities.

3 For each of the following quantities, state whether it is a scalar or a vector.

a velocity
b position
c distance
d force
e time
f speed
g acceleration

Apply

4 Draw vector diagrams for the following forces using a scale of 1 cm = 2 N.

a 4 N right
b 10 N left
c 8 N right

5 Draw vector diagrams for the following displacements using a scale of 1 cm = 1 m.

a 2 m down
b 5 m up

6 Rewrite the vectors in question **5** with sign notation using up is positive (+) and down is negative (–).

Analyse

7 Determine the resultant vector when the following are combined: 2 m west, 5 m east and 7 m west.

8 Add the following vectors to determine the resultant vector: 3 m up, 2 m down and 3 m down.

9 Determine the resultant vector of a toy train that is made to move in these directions: 23 m forwards, 16 m backwards, 7.0 m forwards and 3.0 m backwards.

10 When adding vector B to vector A using the head-to-tail method, determine the points between which the resultant vector is drawn.

11 Determine the change in velocity of a runner who changes from running at $4\,m\,s^{-1}$ to the right on grass to running $2\,m\,s^{-1}$ to the right on sand.

12 Jamelia applies the brakes on her car and changes her velocity from $22.2\,m\,s^{-1}$ forwards to $8.20\,m\,s^{-1}$ forwards. Calculate the change in velocity of Jamelia's car.

6.2 Distance and displacement

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that the motion of an object can be simplified by considering its centre of mass
- describe the concept of displacement
- understand the difference between position, distance and displacement
- calculate the distance travelled by and the displacement of an object.

To analyse and communicate ideas about motion, it is important to understand the terms used to describe motion, even in its simplest form. In this module you will learn about some of the terms used to describe **rectilinear** motion, or straight-line motion, such as position, distance, displacement, speed and velocity.

CENTRE OF MASS

When analysing motion, many real-life examples are complex, so you might need to simplify the situation. For example, as a freestyle swimmer travels at a constant speed of $2\,m\,s^{-1}$, their head and torso move forwards at this speed. The motion of their arms, however, is more complex. At times their arms move forwards through the air faster than $2\,m\,s^{-1}$, and at other times they are moving backwards through the water.

It is beyond the scope of this course to analyse such a complex motion. However, the motion of the swimmer can be simplified by treating the swimmer as a simple object located at a single point called the **centre of mass**. The centre of mass is the balance point of an object. For a person, the centre of mass is located near the waist. The centres of mass of some everyday objects are shown in Figure 6.2.1.

FIGURE 6.2.1 The centre of mass of each object is indicated by a cross.

Position, distance and displacement

The terms 'position', 'distance' and 'displacement' are often used interchangeably in everyday language. But in physics they have specific meanings used to describe an object's relative location and movement.

Position

One important term to understand when analysing straight line motion is position.

- **Position** describes the location of an object at a certain point in time with respect to the origin.
- Position is a vector quantity and therefore requires a direction.

Consider a swimmer, Sophie, doing laps in a 50 m pool, as shown in Figure 6.2.2. To simplify her motion, Sophie is treated as a simple point object. The pool can be treated as a one-dimensional number line, with the starting block as the origin. The direction to the right of the starting block is taken to be positive.

In Figure 6.2.2a, Sophie's position as she is warming up behind the starting block is −10 m. The negative sign indicates the direction from the origin, which is to the left. Her position could also be given as 10 m to the left of the starting block.

In Figure 6.2.2b, Sophie's position at the starting block is 0 m.

In Figure 6.2.2c, Sophie's position after swimming half a length of the pool is +25 m or 25 m to the right of the origin.

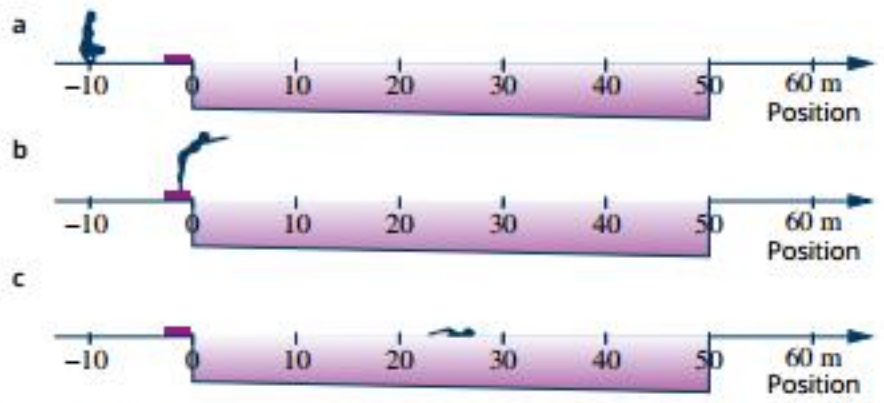


FIGURE 6.2.2 The position of the swimmer is given with reference to the starting block. (a) While warming up, Sophie is at −10 m. (b) When she is on the starting block, her position is zero. (c) After swimming for a short time, she is at a position of +25 m.

Distance travelled

Position describes where an object is at a certain point in time. However, **distance travelled** is how far a body travels during a journey.

In Figure 6.2.2, if Sophie completes three lengths of the pool, the distance travelled during her swim will be:

$$50 + 50 + 50 = 150\,\text{m}$$

The distance travelled is not affected by the direction of the motion. That is, the distance travelled by an object always increases as it moves, regardless of its direction. The tripmeter or odometer of a car or bike measures distance travelled.

Distance travelled, *d*, describes the length of the path covered during an object's entire journey.

Distance travelled is a scalar quantity and is measured in metres (m).

Displacement

Displacement, *s*, is defined as the change in position of an object. Displacement considers only where the motion starts and finishes. The route taken between these points has no effect on displacement. The sign of the displacement indicates the direction in which the position has changed from the start to the end.

Consider the example of Sophie completing one length of the pool. After one lap, the distance travelled is 50 m. Her final position is +50 m and her initial position is 0 m. Her displacement is:

s = final position − initial position
= 50 − 0
= +50 m

Sophie's displacement is 50 m in a positive direction.

Recall that magnitude, units and direction are required for a vector quantity. The distance will be equal to the magnitude of the displacement only if the body is moving in a straight line and does not change direction. If Sophie swims two lengths, her distance travelled will be 100 m: 50 m out and 50 m back. However, her displacement during this swim will be:

s = final position − initial position
= 0 − 0
= 0 m

Even though Sophie has swum 100 m, her displacement is zero because the initial and final positions are the same.

Displacement, *s*, is the change in position of an object in a given direction.

Displacement is a vector quantity and is measured in metres (m).

s = final position − initial position

The above formula for displacement is useful if you already know the initial and final positions of a body's motion. An alternative method to determine total displacement, if you know the displacement of each section of the motion, is to add up the individual displacements for each section of motion.

Total displacement = sum of individual displacements

It is important to remember that displacement is a vector and so, when adding displacements, you must obey the rules of vector addition (discussed in Module 6.1).

If Sophie completed two laps, her overall displacement could have been calculated by adding the displacement of each lap:

s = sum of displacements for each lap
= 50 m in the positive direction + 50 m in the negative direction
= 50 + (−50)
= 0 m

6.2 Review

SUMMARY

- The motion of an object travelling in a straight line is known as rectilinear motion.
- Position describes the location of an object with respect to a defined origin.
- Distance travelled, *d*, tells us how far an object has travelled. Distance travelled is a scalar.
- Displacement, *s*, is a vector and is described as the change in position of an object in a given direction:

  s = final position – initial position
- The centre of mass is a single balance point of an object. This point can be used to simplify the motion of an object.

KEY QUESTIONS

Describe

1 Recall the expression for displacement.

2 Identify whether displacement is a scalar or a vector quantity.

3 Contrast displacement and distance travelled.

Apply

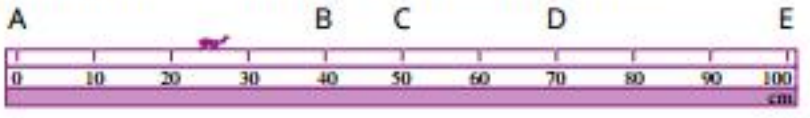
4 A girl swims 10 lengths of a 25 m pool. Determine her:
- **a** distance travelled
- **b** displacement.

5 Describe a scenario in which an object could have a distance travelled of 100 m but a displacement of –20 m.

6 Sketch the path of a student who has walked 20 m north then 10 m south. Label the distance and displacement.

Analyse

7 A somewhat confused ant is walking back and forth along a metre ruler, as show in the figure below. Determine both the size of the displacement and the distance travelled by the ant as it travels on the following paths, taking the right as positive.



- **a** A to B
- **b** C to B
- **c** C to D
- **d** C to E and then to D

8 During a training ride, a cyclist rides 50.0 km north then 30.0 km south.
- **a** Calculate the distance travelled by the cyclist during the ride.
- **b** Calculate the displacement of the cyclist for this ride.

9 A train leaves station A and travels 8 km north to station B. It then travels 25 km north to station C before travelling 38 km south to return to the train yard.

Calculate the:
- **a** distance travelled by the train during the journey
- **b** displacement of the train for this journey.

6.3 Speed and velocity

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the concept of velocity
- understand the difference between speed and velocity
- compare instantaneous velocity and average velocity
- calculate the average velocity of an object
- convert between $km\,h^{-1}$ and $m\,s^{-1}$.

For thousands of years, humans have tried to travel at ever greater speeds. This desire has contributed to the development of all sorts of competitive activities, as well as major advances in engineering and design. World records for some of these pursuits are given in Table 6.3.1.

TABLE 6.3.1 World record speeds for a variety of sports or modes of transport

Activity	World record speed ($m\,s^{-1}$)	World record speed ($km\,h^{-1}$)
racehorse	19.7	71
luge	43	140
cricket delivery	44.7	161
waterskiing (barefoot)	68.3	246
tennis serve	73.1	263
train	161	575

Speed and velocity are both quantities that give an indication of how quickly the position of an object is changing. Both terms are in common use and are often assumed to have the same meaning. In physics, however, these two terms have different definitions.

Instantaneous speed and velocity

Instantaneous speed and **instantaneous velocity** give a measure of how fast something is moving at a particular point in time. The speedometer on a car or bike indicates instantaneous speed.

If a speeding car is travelling north and is detected on a police radar gun at $150\,km\,h^{-1}$, it indicates that this car's instantaneous speed is $150\,km\,h^{-1}$, while its instantaneous velocity is $150\,km\,h^{-1}$ north. Notice that the instantaneous speed is equal to the magnitude of the instantaneous velocity; however, the quantity for instantaneous velocity also includes a direction. This is always the case for instantaneous speed and velocity.

Average speed and velocity

Average speed and **average velocity** both give an indication of how fast an object is moving over a time interval.

average speed, $v_{av} = \dfrac{\text{total distance}}{\text{time taken}} = \dfrac{d}{\Delta t}$

average velocity, $v_{av} = \dfrac{\text{displacement}}{\text{time taken}} = \dfrac{s}{\Delta t}$

- Speed is described in terms of the rate at which the distance is travelled. Like distance, speed is a scalar. A direction is not required when describing the speed of an object.
- Velocity is described in terms of the rate at which displacement changes, and so is a vector quantity. A direction should always be given with a velocity.
- The SI unit for speed and velocity is metres per second ($m\,s^{-1}$); kilometres per hour ($km\,h^{-1}$) is also commonly used, so always check the units. See the Skillbuilder on page 212 for practice in converting between the two units.

FIGURE 6.3.1 Anna Meares won the UCI world championship in 2013. She rode 500 m in a world record time of 32.836 s. Her average speed was 55.6 km h^{-1} but her average velocity was zero.

Average speed is equal to instantaneous speed only when a body is moving in uniform motion (that is, if it moves at a constant speed).

The average speed of a car that takes 30 minutes to travel 20 km from the University of Queensland to Brisbane Airport is 40 km h^{-1}. However, this does not mean that the car travelled the whole distance at this speed. In fact, it is more likely that the car was mainly moving at 60 km h^{-1}, but then for some of the time the car would not be moving at all.

A direction (such as north, south, up, down, left, right, positive, negative) must be given when describing a velocity. The direction will always be the same as that of the displacement. Like the relationship between distance and displacement, average speed will be equal to the magnitude of average velocity only if the body is moving in a straight line and does not change direction.

For example, in a complete lap of a circular track such as the velodrome shown in Figure 6.3.1, regardless of the average speed, the magnitude of the average velocity will be zero, because the displacement is zero.

SKILLBUILDER

Converting units

The SI unit for velocity is m s^{-1}, but km h^{-1} is often used, so it is important to understand how to convert between the two units.

Converting km h^{-1} to m s^{-1}

You should be familiar with 100 km h^{-1}, as it is the speed limit for most freeways and country roads in Australia. Cars that maintain this speed would travel 100 km in 1 hour which is the same as travelling 100 000 m in 3600 s, as there are 1000 metres in 1 kilometre and 3600 seconds in 1 hour (60 s × 60 min).

$$\begin{aligned} 100\,\text{km h}^{-1} &= 100 \times 1000\,\text{m h}^{-1} \\ &= 100\,000\,\text{m h}^{-1} \\ &= \frac{100\,000}{3600}\,\text{m s}^{-1} \\ &= 27.8\,\text{m s}^{-1} \end{aligned}$$

So km h^{-1} can be converted to m s^{-1} by multiplying by $\frac{1000}{3600}$ (or dividing by 3.6).

Converting m s^{-1} to km h^{-1}

A champion Olympic sprinter can run at an average speed of close to 10 m s^{-1}. Each second, the athlete will travel approximately 10 m. At this rate, in 1 hour the athlete would travel:

$10 \times 3600 = 36\,000\,\text{m} = 36\,\text{km}$

To convert 10 m s^{-1} into km h^{-1}:

$$\begin{aligned} 10\,\text{m s}^{-1} &= 10 \times 3600\,\text{m h}^{-1} \\ &= 36\,000\,\text{m h}^{-1} \\ &= \frac{3600}{1000}\,\text{km h}^{-1} \\ &= 36\,\text{km h}^{-1} \end{aligned}$$

So m s^{-1} can be converted to km h^{-1} by multiplying by $\frac{3600}{1000}$ or 3.6.

When converting a speed from one unit to another, it is important to think about the speeds to ensure that your answers make sense. The diagram in Figure 6.3.2 summarises the conversion between units for speed.

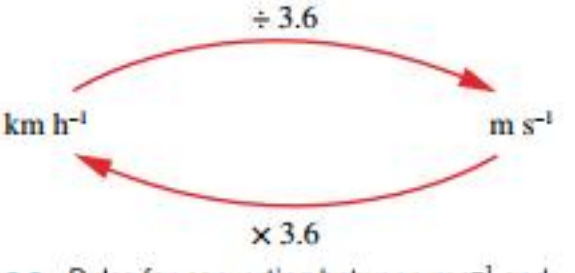


FIGURE 6.3.2 Rules for converting between m s^{-1} and km h^{-1}.

Alternative units for speed

Metres per second is the standard unit for measuring speed because it is derived from the standard unit for distance (metres) and the standard unit for time (seconds). However, alternative units are often used to better suit a certain application.

The speed of a boat is usually measured in knots, where 1 knot = 0.51 m s^{-1}. This unit originated in the 17th century, when the speed of sailing vessels would be measured by allowing a rope, with knots tied at regular intervals, to be dragged by the water through a sailor's hands. The speed of the boat could be estimated by counting the number of knots that passed through the sailor's hands, while measuring the time taken for this to happen, and then applying the average speed formula.

The speed of very fast aeroplanes, as shown in Figure 6.3.3, can be measured in Mach numbers. One Mach (referred to as Mach 1) is equal to the speed of sound, which is 340 m s^{-1}. Mach 2 is equal to 680 m s^{-1}, or twice the speed of sound.

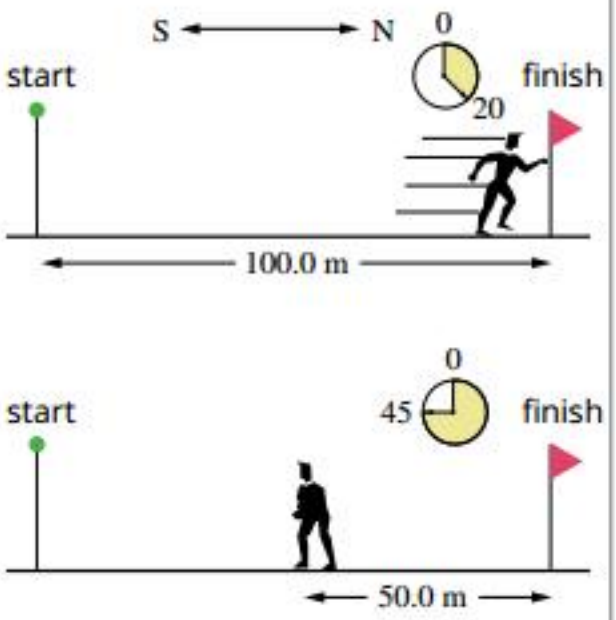
FIGURE 6.3.3 Modern fighter aeroplanes can fly at speeds above Mach 1.

Worked example 6.3.1

AVERAGE VELOCITY AND CONVERTING UNITS

Sam is an athlete performing a training routine by running back and forth along a straight stretch of running track. He jogs at a consistent pace 100.0 m north in 20.0 s, then turns and walks 50.0 m south for a further 25.0 s before stopping.

a Calculate Sam's average velocity in m s^{-1}.

Thinking	Working
Calculate the displacement. Remember total displacement is the sum of individual displacements. Sam's total journey consists of two displacements: 100.0 m north and then 50.0 m south.	s = sum of displacements = 100.0 m north + 50.0 m south = 100.0 + (–50.0) = +50.0 m or 50.0 m north 
Work out the total time taken for the journey.	20.0 + 25.0 = 45.0 s
Substitute the values into the velocity equation. Displacement is 50.0 m north. Time taken is 45.0 s.	$v_{av} = \frac{s}{\Delta t}$ $= \frac{50.0}{45.0}$ = +1.11 m s^{-1}
Use the sign convention to state the answer with its direction.	1.11 m s^{-1} north

b Calculate the magnitude of Sam's average velocity in $km\,h^{-1}$.	
Thinking	**Working**
Convert from $m\,s^{-1}$ to $km\,h^{-1}$ by multiplying by 3.6.	$v_{av} = 1.1\,m\,s^{-1} = 1.1 \times 3.6$ $= 4.0\,km\,h^{-1}$ north
As the magnitude of velocity is needed, direction is not required in this answer.	Magnitude of $v_{av} = 4.0\,km\,h^{-1}$
c Calculate Sam's average speed in $m\,s^{-1}$.	
Thinking	**Working**
Calculate the distance. Remember distance is the length of the path covered in the entire journey. The direction does not matter. Sam travels 100.0 m in one direction and then 50.0 m in the other direction.	$d = 100.0 + 50.0$ $= 150.0$
Work out the total time taken for the journey.	$20.0 + 25 = 45\,s$
Substitute the values into the speed equation. Distance is 150.0 m. Time taken is 45 s.	$v_{av} = \frac{d}{\Delta t}$ $= \frac{150.0}{45.0}$ $= 3.33\,m\,s^{-1}$
d Calculate Sam's average speed in $km\,h^{-1}$.	
Thinking	**Working**
Convert from $m\,s^{-1}$ to $km\,h^{-1}$ by multiplying by 3.6.	$v_{av} = 3.33\,m\,s^{-1}$ $= 3.33 \times 3.6$ $= 12.0\,km\,h^{-1}$
Speed is not a vector, so a direction is not given.	$12.0\,km\,h^{-1}$
e Sam's smartwatch recorded his fastest instantaneous velocity of $5.30\,m\,s^{-1}$ north. Contrast Sam's average velocity to his instantaneous velocity and recognise any differences.	
Thinking	**Working**
Contrast the magnitude and direction of Sam's average and instantaneous velocities.	$v_{av} = 1.11\,m\,s^{-1}$ north $v_{instantaneous} = 5.30\,m\,s^{-1}$ north The magnitude of Sam's instantaneous velocity is greater than that of his average velocity.
Recognise any differences due to changes in speed or direction of his movements.	The differences between these two velocities are due to the fact Sam did not have a constant speed or direction during his training. His instantaneous velocity would be slower during his walk, and he walked in the opposite direction to his jog, which would reduce his average velocity.

➤ Try yourself 6.3.1

AVERAGE VELOCITY AND CONVERTING UNITS

Sally is an athlete performing a training routine by running back and forth along a straight stretch of running track. She jogs at a consistent pace 100.0 m west in 20.0 s, then turns and walks 160.0 m east in a further 45.0 s before stopping.

a Calculate Sally's average velocity in $m\,s^{-1}$.

b Calculate the magnitude of Sally's average velocity for the entire journey in $km\,h^{-1}$.

c Calculate Sally's average speed in $m\,s^{-1}$.

d Calculate Sally's average speed in $km\,h^{-1}$.

e Sally's smartwatch recorded her fastest instantaneous velocity of $5.7\,m\,s^{-1}$ west. Contrast Sally's average velocity to her instantaneous velocity and recognise any differences.

6.3 Review

SUMMARY

- The average speed of a body, v_{av}, is described as the rate of change of distance and is a scalar quantity:

$$\text{average speed, } v_{av} = \frac{\text{total distance}}{\text{time taken}} = \frac{d}{\Delta t}$$

- The average velocity of a body, v_{av} is described as the rate of change of displacement and is a vector quantity:

$$\text{average velocity, } v_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{s}{\Delta t}$$

- The SI unit for both speed and velocity is metres per second ($m\,s^{-1}$).
- To convert from $m\,s^{-1}$ to $km\,h^{-1}$, multiply by 3.6.
- To convert from $km\,h^{-1}$ to $m\,s^{-1}$, divide by 3.6.
- The instantaneous velocity of an object relates to the position of the object at a particular point in time.
- The average velocity of an object relates to the total displacement of the object over a set period.

KEY QUESTIONS

Describe

1 State the formula for:
- **a** average speed
- **b** average velocity.

2 Recall how to convert $m\,s^{-1}$ into $km\,h^{-1}$.

3 Recall how to convert $km\,h^{-1}$ into $m\,s^{-1}$.

Apply

4 Contrast speed and velocity.

5 Contrast instantaneous velocity and average velocity.

6 Explain how the driver of a car travelling with an average speed of $100\,km\,h^{-1}$ recalls seeing a speed of $120\,km\,h^{-1}$ on the speedometer.

7 Explain how a car travelling with an average speed of $100\,km\,hr^{-1}$ has an average velocity of $80\,km\,hr^{-1}$.

Analyse

8 A cyclist travels 25 km in 90.0 minutes.
- **a** Calculate her average speed in $km\,h{-}^{1}$.
- **b** Calculate her average speed in $m\,s{-}^{1}$.

9 Liam pushes his toy truck 5.0 m east, then stops it and pushes it 4.0 m west. The entire motion takes 10.0 s.
- **a** Calculate the average speed of the truck.
- **b** Calculate the average velocity of the truck.

10 A student is carrying a heavy tub of books from the class to the library. They walk at a constant pace for 20 m north over 12 seconds before putting the tub down to rest for 10 seconds. They then travel the last 20 m north over 15 seconds.
- **a** Calculate their instantaneous velocity 10 s into their journey.
- **b** Calculate their average velocity for the total journey.
- **c** Contrast the instantaneous velocity to their average velocity.

6.4 Acceleration

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe acceleration as a change in velocity over a particular time period
- calculate the acceleration of an object.

If you have been on a train as it pulled out of the station, you have experienced acceleration. If you have been in an aircraft as it has taken off from a runway, you will have experienced a much greater acceleration. Astronauts and fighter pilots experience enormous accelerations that would make an untrained person lose consciousness. **Acceleration**, which is a measure of how quickly velocity changes, will be discussed in this module.

FINDING THE CHANGE IN VELOCITY AND SPEED

A car speeding away as the traffic lights turn green, a runner stopping at the end of a race, a bouncing tennis ball and a rollercoaster carriage on a ride all involve changing velocities. If the initial velocity and final velocity of an object are known, then the change in velocity can be calculated.

To find the change, Δ, in any physical quantity, including speed and velocity, the initial value is taken away from the final value. Vector subtraction was covered in detail in Module 6.1.

Finding the change in speed is the same process as finding the change in velocity, where change in speed is the final speed minus the initial speed ($\Delta v = v - u$). As speed is a scalar, direction is not considered.

Change in velocity is the final velocity minus the initial velocity:

$\Delta v = v - u$

where

u is the initial velocity ($m\,s^{-1}$)

v is the final velocity ($m\,s^{-1}$)

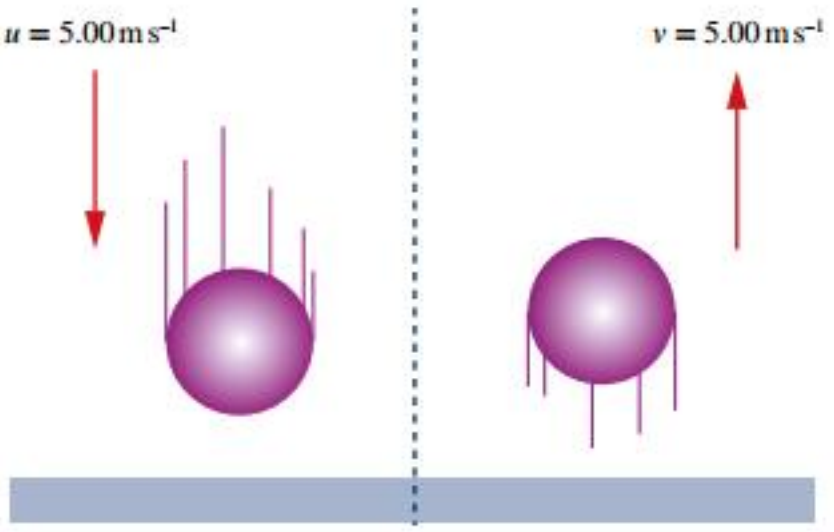
Δv is the change in velocity ($m\,s^{-1}$)

Velocity is a vector, so perform a vector subtraction. As for all vectors, direction is required.

Worked example 6.4.1

CHANGE IN SPEED AND VELOCITY

A golf ball is dropped onto a concrete floor and strikes the floor at $5.00\,m\,s^{-1}$. It then rebounds at $5.00\,m\,s^{-1}$.



a Calculate the change in speed of the ball.

Thinking	Working
Find the values for the initial speed and the final speed of the ball.	$u = 5.00\,m\,s^{-1}$ $v = 5.00\,m\,s^{-1}$
Substitute the values into the change in speed equation: $\Delta v = v - u$	$\Delta v = v - u$ $= (5.00) - (5.00)$ $= 0\,m\,s^{-1}$

b Calculate the change in velocity of the ball.	
Thinking	**Working**
Velocity is a vector. Apply the sign convention to replace the directions.	$u = 5.00\,m\,s^{-1}$ down $= -5.00\,m\,s^{-1}$ $v = 5.00\,m\,s^{-1}$ up $= +5.00\,m\,s^{-1}$
As this is a vector subtraction, reverse the direction of u to get $-u$.	$u = -5.00\,m\,s^{-1}$ $-u = +5.00\,m\,s^{-1}$
Substitute the values into the change in velocity equation: $\Delta v = v + (-u)$	$\Delta v = v + (-u)$ $= (+5.00) + (+5.00)$ $= +10.0\,m\,s^{-1}$
Apply the sign convention to describe the direction.	$v = 10.0\,m\,s^{-1}$ up

➤ Try yourself 6.4.1

CHANGE IN SPEED AND VELOCITY

A golf ball is dropped onto a concrete floor and strikes the floor at $9.00\,m\,s^{-1}$. It then rebounds at $7.00\,m\,s^{-1}$.

a Calculate the change in speed of the ball.

b Calculate the change in velocity of the ball.

ACCELERATION

Consider the following information about the velocity of a car that starts from rest, as shown in the Figure 6.4.1. The velocity of the car (Figure 6.4.1) increases by $10\,km\,h^{-1}$ each second. In other words, its velocity changes by $+10\,km\,h^{-1}$ per second. This is stated as an acceleration of +10 kilometres per hour per second or $+10\,km\,h^{-1}\,s^{-1}$. More commonly in physics, velocity information is given in metres per second.

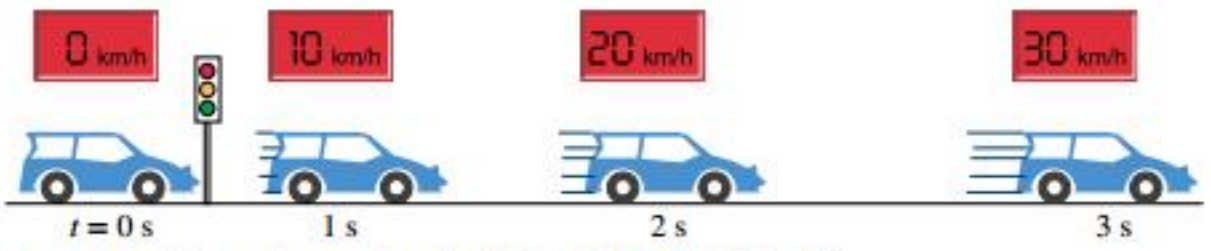


FIGURE 6.4.1 The car increases in velocity from $0\,km\,h^{-1}$ to $30\,km\,h^{-1}$.

The athlete in Figure 6.4.2 below takes 3 seconds to come to a stop at the end of a race.

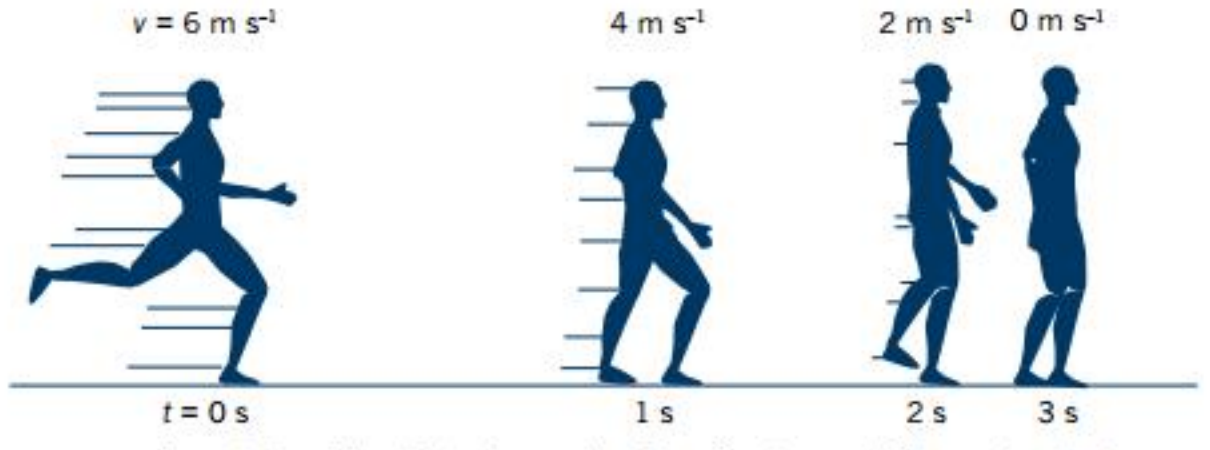


FIGURE 6.4.2 The velocity of the athlete changes by $-2\,m\,s^{-1}$ each second. The acceleration is $-2\,m\,s^{-2}$.

The velocity of the athlete changes by $-2\,m\,s^{-1}$ each second, so the acceleration is −2 metres per second per second. This is usually expressed as −2 metres per second squared or $-2\,m\,s^{-2}$.

A negative acceleration can mean that the object is slowing down in the direction of travel, as in the case of the athlete in Figure 6.4.2. A negative acceleration can also mean speeding up but in the opposite direction.

Acceleration is a vector quantity, so vector diagrams can be used to calculate resultant accelerations of an object.

Average acceleration

As with speed and velocity, the average acceleration of an object can also be calculated.

Average acceleration, a_{av}, is the rate of change of velocity:

$$a_{av} = \frac{\text{change in velocity}}{\text{time taken}}$$

$$= \frac{\Delta v}{\Delta t}$$

$$= \frac{v - u}{\Delta t}$$

where

v is the final velocity ($m\,s^{-1}$)

u is the initial velocity ($m\,s^{-1}$)

Δt is the time interval (s).

Worked example 6.4.2

AVERAGE ACCELERATION

A golf ball is dropped onto a concrete floor and strikes the floor at $5.0\,m\,s^{-1}$. It then rebounds at $5.0\,m\,s^{-1}$. The contact with the floor lasts for a time of 25 ms.
Calculate the average acceleration of the ball during its contact with the floor.

Thinking	Working
Note the values you will need in order to find the average acceleration (initial velocity, final velocity and time). Let up be the positive direction. Convert ms into s by dividing by 1000.	$u = -5.0\,m\,s^{-1}$ $-u = 5.0\,m\,s^{-1}$ $v = 5.0\,m\,s^{-1}$ $\Delta v = v + (-u)$ $= (+5.0) + (+5.0)$ $= +10.0\,m\,s^{-1}$ $\Delta t = 25\,ms$ $= 0.025\,s$
Substitute the values into the average acceleration equation.	$a_{av} = \frac{\Delta v}{\Delta t}$ $= \frac{10.0}{0.025}$ $= +4.0 \times 10^2\,m\,s^{-2}$
Use the sign convention to state the answer with its direction.	$= 4.0 \times 10^2\,m\,s^{-2}$ up

➤ Try yourself 6.4.2

AVERAGE ACCELERATION

A golf ball is dropped onto a concrete floor and strikes the floor at $9.0\,m\,s^{-1}$. It then rebounds at $7.0\,m\,s^{-1}$. The contact time with the floor is 35 ms.
Calculate the average acceleration of the ball during its contact with the floor.

6.4 Review

SUMMARY

- Change in speed is a scalar calculation:

  Δv = final speed – initial speed = $v - u$

- Change in velocity is a vector calculation:

  Δv = final velocity – initial velocity = $v - u$

- Acceleration is a vector. The average acceleration of a body, a_{av}, is described as the rate of change of velocity:

$$a_{av} = \frac{\text{change in velocity}}{\text{time taken}} = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t}$$

- Acceleration is measured in metres per second per second ($m s^{-2}$) or metres per second squared.

KEY QUESTIONS

Describe

1 Recall the units used to measure acceleration.

2 Recall the three properties needed to describe acceleration.

3 State an expression for the average acceleration of an object:

- **a** in words
- **b** in terms of its change in velocity and time
- **c** in terms of its initial and final velocity, and time.

Apply

4 Describe a scenario in which an object travelling in a positive direction would experience positive acceleration from rest.

5 A radio-controlled car is travelling east at $10.0 km h^{-1}$. It hits some sand and slows down to $3.0 km h^{-1}$ east. Qualitatively describe its change in velocity if east is the positive direction.

6 Describe the acceleration experienced by the car in the previous question.

Analyse

7 A lump of putty falls vertically at $5.0 m s^{-1}$ and stops dead when it hits the floor. Calculate its change in velocity during the collision.

8 A ping-pong ball falls vertically at $5.0 m s^{-1}$. When it hits the floor, it rebounds at $3.0 m s^{-1}$ up. Calculate the change in velocity during the bounce.

9 Ashley runs north on a soccer field at $7.5 m s^{-1}$. He slides along the ground and stops in 1.5 s. Calculate his average acceleration as he slides to a stop.

10 A squash ball travelling east at $25 m s^{-1}$ strikes the front wall of the court and rebounds at $15 m s^{-1}$ west. The contact time between the wall and the ball is 0.050 s. Use vector diagrams, where appropriate, to help you with your calculations.

- **a** Calculate the change in speed of the ball.
- **b** Calculate the change in velocity of the ball.
- **c** Calculate the magnitude of the average acceleration of the ball during its contact with the wall.

6.5 Equations of motion

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand and apply equations of motion for objects travelling in a straight line with uniform acceleration
- solve problems relating to uniformly accelerated motion in one dimension
- select the correct equation of motion to use for the known variables
- understand and analyse vertical motion of an object.

This module examines a precise method of solving problems involving constant or uniform acceleration. This method involves the use of a series of equations that can be derived from the basic definitions for displacement, speed and velocity.

EQUATIONS OF MOTION WITH UNIFORM ACCELERATION

Consider an object moving in a straight line with an initial velocity, u, and a uniform acceleration, a, for a time interval, Δt. As u, v and a are vectors, and the motion is limited to one dimension, the sign and direction convention of right as positive and left as negative can be used. After a period of time, Δt, the object has changed its velocity from an initial velocity of u and is now travelling with a final velocity of v.

For scenarios in which an object is moving in a straight line with constant acceleration we can use the following equations, known as the equations of uniformly accelerated motion in one dimension.

$$v_{av} = \frac{1}{2}(u + v)$$

$$v = u + at$$

$$v^2 = u^2 + 2as$$

$$s = ut + \frac{1}{2}at^2$$

These equations are commonly used to solve problems in which acceleration is constant (or uniform).

$v_{av} = \frac{1}{2}(u + v)$

$v = u + at$

$v^2 = u^2 + 2as$

$s = ut + \frac{1}{2}at^2$

where

- s is the displacement (m)
- u is the initial velocity ($m\,s^{-1}$)
- v is the final velocity ($m\,s^{-1}$)
- a is the acceleration ($m\,s^{-2}$)
- t is the time taken (s)
- v_{av} is the average velocity ($m\,s^{-1}$).

SOLVING PROBLEMS USING EQUATIONS

When solving problems using these equations, it is important to think about the problem and try to visualise what is happening. Follow the steps below.

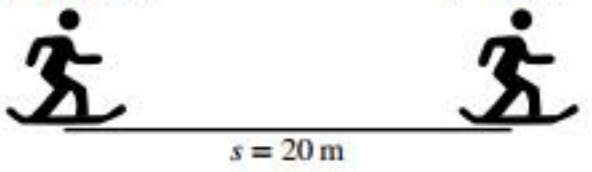
1. Draw a simple diagram of the situation.
2. Write down the information that has been given in the question. You might like to use the word 'suvat' as a memory trick to help you remember to list the variables in the order s, u, v, a and t. Use a sign convention to assign positive and negative values to indicate directions. Convert all units to SI form.
3. Select the equation that matches your data. It should include three values that you know, and the one value that you want to solve.
4. Use the appropriate number of significant figures in your answer.
5. Include units with the answer and specify a direction if the quantity is a vector.

Worked example 6.5.1

USING THE EQUATIONS OF MOTION

A snowboarder in a race is travelling $10.0\,m\,s^{-1}$ north as he crosses the finishing line. He then decelerates uniformly, coming to a stop over 20.0 m.

a Calculate the acceleration of the snowboarder as he comes to a stop.

Thinking	Working
Draw a simple diagram of the scenario.	$u = 10.0\,m\,s^{-1}$ $v = 0\,m\,s^{-1}$ 
Write down the known quantities as well as the quantity you are finding. Apply the sign convention that north is positive, and south is negative. Take all the information from the question. 'Coming to a stop' means that the final velocity is zero. Use equations for constant acceleration.	$s = +20.0\,m$ $u = +10.0\,m\,s^{-1}$ $v = 0\,m\,s^{-1}$ $a = ?$
Identify the correct equation to use.	$v^2 = u^2 + 2as$
Substitute known values into the equation and solve for a. Include units with the answer.	$0^2 = 10.0^2 + 2 \times a \times 20.0$ $0 = 100.0 + 40.0a$ $-100.0 = 40.0a$ $a = \frac{-100.0}{40.0}$ $= -2.50\,m\,s^{-2}$
Use the sign convention to state the answer with its direction.	$a = 2.50\,m\,s^{-2}$ south

b Determine how long the snowboarder takes to come to a stop.

Thinking	Working
Write down the known quantities as well as the quantity you are finding. Apply the sign convention that north is positive, and south is negative. Take all the information from the question. 'Coming to a stop' means that the final velocity is zero. Use equations for constant acceleration.	$s = +20.0\,m$ $u = +10.0\,m\,s^{-1}$ $v = 0\,m\,s^{-1}$ $a = -2.5\,m\,s^{-2}$ $t = ?$
Identify the correct equation to use. You now know four values, so any equation involving t will work.	$v = u + at$
Substitute known values into the equation and solve for t. Include units with the answer.	$v = u + at$ $0 = 10.0 + (-2.5) \times t$ $-10.0 = -2.5t$ $t = \frac{-10.0}{-2.5}$ $= 4.00\,s$

c What is the average velocity of the snowboarder as he comes to a stop?	
Thinking	**Working**
Write down the known quantities as well as the quantity that you are finding. Apply the sign convention that north is positive, and south is negative. The acceleration is constant, so you only need to find the average of the final and initial speeds.	$u = +10.0\,\text{m s}^{-1}$ $v = 0\,\text{m s}^{-1}$ $v_{av} = ?$
Identify the correct equation to use.	$v_{av} = \frac{1}{2}(u + v)$
Substitute known values into the equation and solve for v_{av}. Include units with the answer.	$v_{av} = \frac{1}{2}(u + v)$ $= \frac{1}{2}(0 + 10.0)$ $= +5.00\,\text{m s}^{-1}$
Use the sign convention to state the answer with its direction.	$v_{av} = 5.0\,\text{m s}^{-1}$ north

➤ Try yourself 6.5.1

USING THE EQUATIONS OF MOTION

A snowboarder in a race is travelling $15\,\text{m s}^{-1}$ east as she crosses the finishing line. She then decelerates uniformly until coming to a stop over 30.0 m.

a Calculate the acceleration of the snowboarder as she comes to a stop.

b Determine how long she takes to come to a stop.

c Calculate the average velocity of the snowboarder as she comes to a stop.

VERTICAL MOTION

Until 500 years ago, it was widely believed that the heavier the object, the faster it would fall. This was the theory of Aristotle, and it lasted for 2000 years until the end of the Middle Ages. In the 17th century, the Italian scientist Galileo conducted experiments that showed that the mass of the object did not affect the rate at which it fell, if **air resistance** was not a factor.

It is now known that falling objects speed up because of gravity. Many people still think that heavier objects fall faster than light objects. This is not the case, but the confusion arises because of the effects of air resistance. This module examines the motion of falling objects.

Analysing vertical motion

Air resistance has a significant affect on some falling objects, such as feathers and balloons. This is why these objects do not speed up much as they fall. However, if air resistance is ignored, all objects that are only under the influence of the force due to gravity (known as bodies **in free-fall**) near Earth's surface will move with an equal downwards acceleration. The image in Figure 6.5.1 shows that the apple is accelerating as it falls, because the distance travelled by the apple between each photograph increases. In a vacuum, this rate of acceleration would be the same for a feather, a bowling ball, or any other object; the mass of the object does not matter.

At the Earth's surface, the acceleration due to gravity, g, is $9.8\,m\,s^{-2}$ down and does not depend on whether the body has been thrown upwards or is falling.

For example, a coin that is dropped from rest will be moving at $9.8\,m\,s^{-1}$ after 1 s, at $19.6\,m\,s^{-1}$ after 2 s and so on. Each second its speed increases by $9.8\,m\,s^{-1}$. The motion of a falling coin is illustrated in Figure 6.5.2.

However, if the coin was launched straight up at $19.6\,m\,s^{-1}$, then after 1 s its speed would be $9.8\,m\,s^{-1}$, and after 2 s it would be stationary. In other words, each second it would slow down by $9.8\,m\,s^{-1}$. The motion of a coin thrown vertically upwards is shown in Figure 6.5.3.

So, regardless of whether the coin is falling or has been tossed, its speed changes at the same rate. The speed of the falling coin increases by $9.8\,m\,s^{-1}$ each second and the speed of the rising coin decreases by $9.8\,m\,s^{-1}$ each second. That means that the acceleration of the coin due to gravity is $9.8\,m\,s^{-2}$ downwards in both cases.

The acceleration of a free-falling body is constant, so it is appropriate to use the equations for uniform acceleration. It is necessary to specify whether up or down is positive when doing these problems. You can simply follow the mathematical convention of regarding up as positive, which would mean the acceleration due to gravity would always be $-9.8\,m\,s^{-2}$.

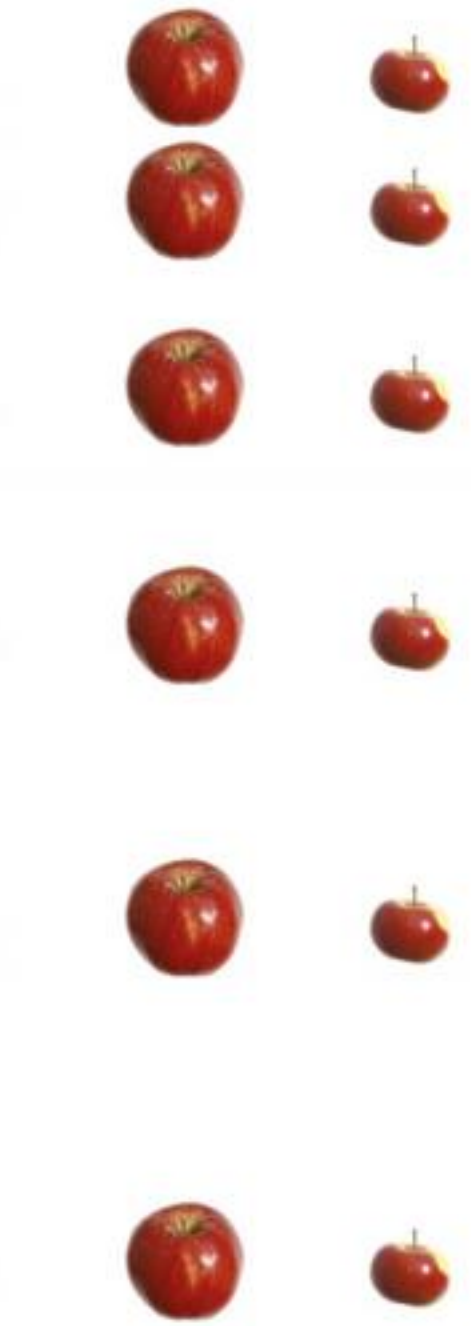


FIGURE 6.5.1 The time elapsed between each image of the free–falling apple is the same but the distance it travels increases, which shows the apple is accelerating. Without air resistance, this rate of acceleration is the same for all objects, regardless of their size.

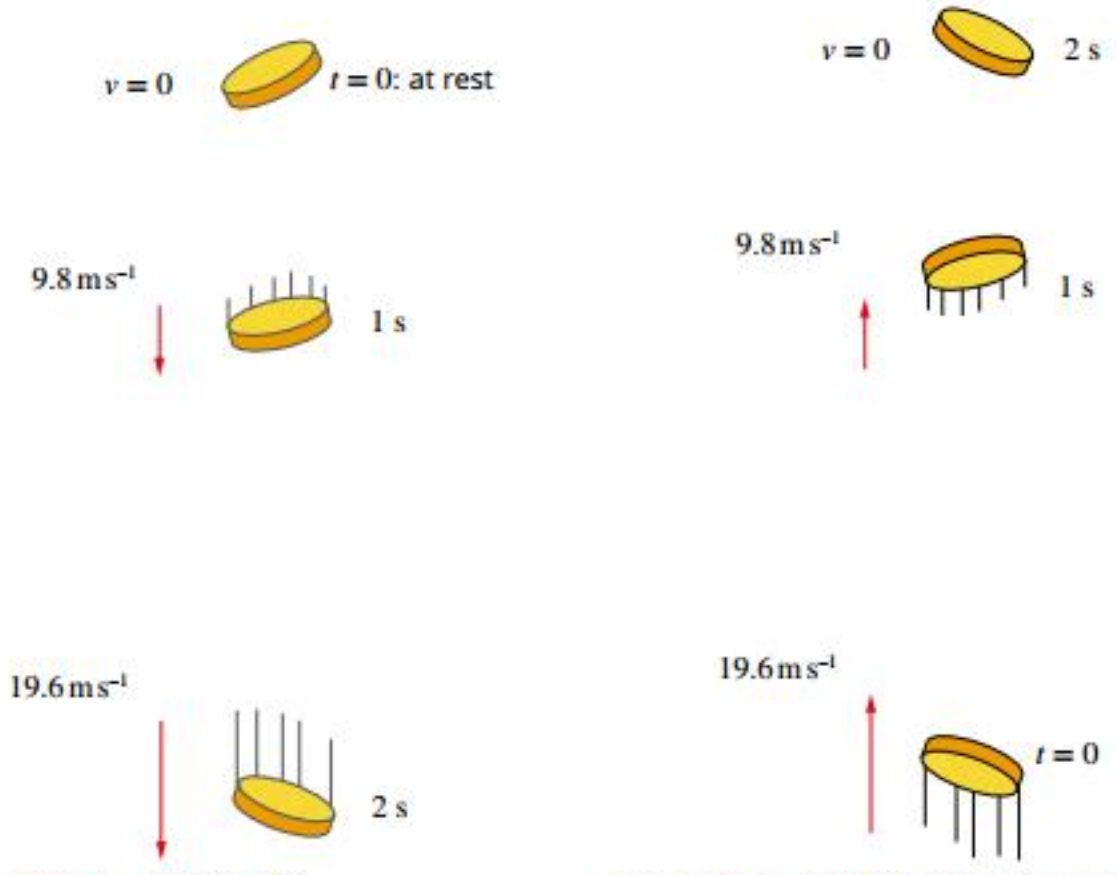


FIGURE 6.5.2 A falling coin

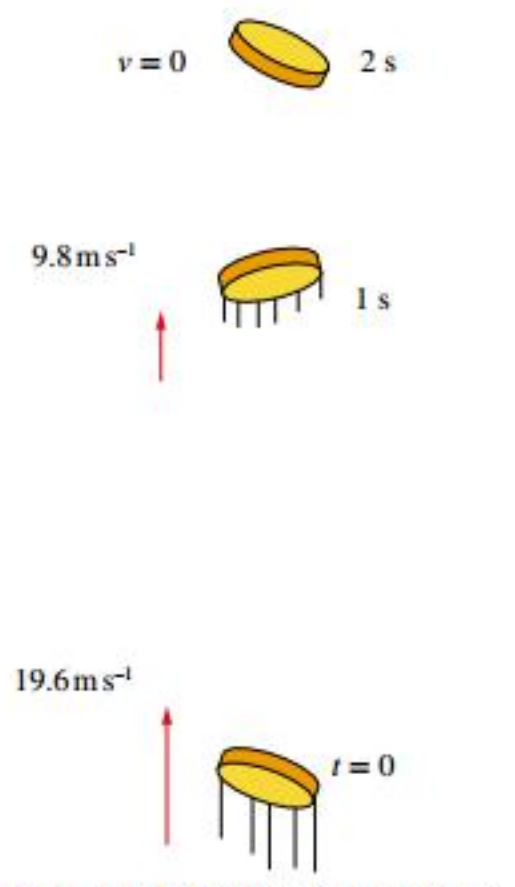


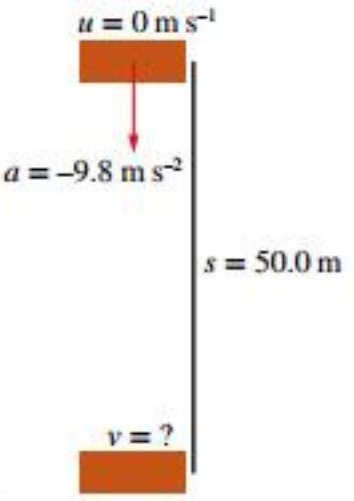
FIGURE 6.5.3 A coin thrown vertically upwards

Worked example 6.5.2

VERTICAL MOTION

A construction worker accidentally knocks a brick from a building so that it falls vertically a distance of 50.0 m to the ground.
Use $g = -9.8\,m\,s^{-2}$ and ignore air resistance when answering these questions.

a Calculate how long it takes for the brick to fall halfway to 25 m.

Thinking	Working
Draw a simple diagram of the scenario.	
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative.	The brick starts at rest so $u = 0$. To fall halfway: $s = -25\,m$ $u = 0\,m\,s^{-1}$ $a = -9.8\,m\,s^{-2}$ $t = ?$
Select the equation for uniform acceleration that best fits the data you have.	$s = ut + \frac{1}{2}at^2$
Substitute known values into the equation and solve for t. Think about whether the value seems reasonable.	$-25 = 0 \times t + \frac{1}{2} \times (-9.8) \times t^2$ $= -4.90t^2$ $t = \sqrt{\frac{-25}{-4.90}}$ $= 2.3\,s$

b Calculate how long it takes the brick to fall all the way to the ground.

Thinking	Working
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative.	To fall the whole way: $s = -50.0\,m$ $u = 0\,m\,s^{-1}$ $a = -9.8\,m\,s^{-1}$ $t = ?$
Identify the correct equation of uniform acceleration to use.	$s = ut + \frac{1}{2}at^2$
Substitute known values into the equation and solve for t. Think about whether the value seems reasonable. Notice that the brick takes 2.3 s to travel the first 25 m and only 0.9 s to travel the final 25 m. This is because it is accelerating.	$-50 = 0 \times t + \frac{1}{2} \times (-9.8) \times t^2$ $-50 = -4.9t^2$ $t = \sqrt{\frac{-50}{-4.9}}$ $= 3.2\,s$

c Calculate the speed of the brick as it hits the ground.	
Thinking	**Working**
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative	$s = -50.0\,\text{m}$ $u = 0\,\text{m s}^{-1}$ $v = ?$ $a = -9.8\,\text{m s}^{-1}$ $t = 3.2\,\text{s}$
Identify the correct equation to use. You now know four values, so any equation involving v will work.	$v = u + at$
Substitute known values into the equation and solve for v. Think about whether the value seems reasonable.	$v = 0 + (-9.8) \times 3.2$ $= -31\,\text{m s}^{-1}$
Use the sign and direction convention to describe the direction of the final velocity.	$v = 31\,\text{m s}^{-1}$ downwards

➤ Try yourself 6.5.2

VERTICAL MOTION

A construction worker accidentally knocks a hammer from a building. The hammer falls vertically a distance of 60.0 m to the ground. Use $g = -9.8\,\text{m s}^{-2}$ and ignore air resistance when answering these questions.

a Calculate how long it takes the hammer to fall halfway to 30.0 m.

b Calculate how long it takes the hammer to fall all the way to the ground.

c Determine the speed of the hammer as it hits the ground.

When an object is thrown vertically up into the air, it will eventually reach a point where it stops momentarily before returning down. So, the velocity of the object decreases as the object rises, becomes zero at the maximum height, and then increases again as the object falls. Throughout this motion, however, the object is still in the same gravitational field, so g remains at $-9.8\,\text{m s}^{-2}$ throughout the journey. Knowing that the velocity of an object thrown in the air is zero at the top of its flight allows you to calculate the maximum height reached.

6.5 Review

SUMMARY

- The following equations can be used for situations with constant acceleration:

$$v_{av} = \frac{1}{2}(u + v)$$
$$v = u + at$$
$$v^2 = u^2 + 2as$$
$$s = ut + \frac{1}{2}at^2$$

- A sign and direction convention for motion in one dimension needs to be used with these equations.
- If air resistance can be ignored, all bodies falling freely near the Earth will move with the same constant acceleration.
- The acceleration due to gravity is represented by g and is equal to $9.8\,m\,s^{-2}$ in the direction towards the centre of Earth.
- The equations for uniform acceleration can be used to solve vertical motion problems. It is necessary to specify whether up or down is positive.

KEY QUESTIONS

Describe

1 Recall an equation of motion in terms of the following variables:
- **a** final velocity, initial velocity, acceleration and time
- **b** time, acceleration, initial velocity and displacement
- **c** displacement, initial velocity, final velocity, acceleration.

2 State the two conditions required to use the equations of motion in the previous question.

3 Recall the magnitude and direction for acceleration due to gravity that can be used to solve vertical motion problems for falling objects.

Apply

4 A cyclist has a uniform acceleration as he rolls down a hill. His initial speed is $5.00\,m\,s^{-1}$, he travels a distance of 30.0 m and his final speed is $18.0\,m\,s^{-1}$. Identify the equation of motion that should be used to determine his acceleration.

5 A ball is thrown upwards with an initial velocity of $25.0\,m\,s^{-1}$. State the ball's instantaneous velocity at its maximum height.

6 A coin is flipped with an initial velocity of $2.5\ m\,s^{-1}$ straight up and caught when it returns to the same height. State the coin's final velocity just before it is caught.

7 A car accelerates from rest at a rate of $2.3\ m\,s^{-2}$ over a period of 4.0 s. Identify the equation of motion that should be used to determine its displacement.

Analyse

For the remaining questions, ignore the effects of air resistance and assume that the acceleration due to gravity is $9.8\,m\,s^{-2}$ down unless instructed otherwise.

8 A window cleaner working on the Infinity tower accidentally drops her mobile phone. The phone falls vertically towards the ground with an acceleration of $9.8\,m\,s^{-2}$.
- **a** Determine the speed of the phone after 3.0 s.
- **b** Calculate how fast the phone is moving after it has fallen 30.0 m.
- **c** Calculate the average velocity of the phone during a fall of 30.0 m.

9 A super ball is bounced so that it travels straight up into the air, reaching its highest point after 1.5 s.
- **a** Calculate the velocity of the ball as it reaches its highest point.
- **b** Calculate the initial speed of the ball just as it leaves the ground.
- **c** Determine the maximum height reached by the ball.

10 A book is knocked off a bench and falls vertically to the floor. It takes 0.40 s to fall to the floor.
- **a** Determine the book's speed as it lands.
- **b** Determine the height from which the book fell.
- **c** Calculate how far the book fell during the first 0.20 s.
- **d** Calculate how far the book fell during the final 0.20 s.

11 A new-model Subaru car travels with a uniform acceleration on a racetrack. It starts from rest and covers 400.0 m in 16 s.

- **a** Calculate the magnitude of its average acceleration during this time.
- **b** Calculate the final speed of the car in $m s^{-1}$.
- **c** Determine the car's final speed in $km h^{-1}$.

12 A hybrid car starts from rest and accelerates uniformly in a positive direction for 8.0 s. It reaches a final speed of $16 m s^{-1}$.

- **a** Calculate the magnitude of the acceleration of the car.
- **b** Calculate the magnitude of the average velocity of the car.
- **c** Calculate the distance travelled by the car.

13 A car is travelling along a straight road at $75 km h^{-1}$ east. To avoid an accident, the motorist brakes suddenly and stops the car.

- **a** Calculate the car's initial speed in $m s^{-1}$.
- **b** Determine the distance the car travels while the driver is reacting to apply the brakes, if the reaction time of the motorist is 0.25 s.
- **c** Once the brakes are applied, the car has an acceleration of $-6.0 m s^{-2}$. Determine how far the car travels while coming to a stop.
- **d** Calculate the total distance the car travels from the time the driver first notices the danger to when the car comes to a stop.

6.6 Graphs of motion

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- interpret position–time graphs to describe an object's motion and its velocity
- interpret velocity–time graphs to describe an object's motion, its acceleration, and its displacement and distance travelled
- interpret acceleration–time graphs to describe an object's motion and its average velocity
- use vertical error bars and minimum and maximum lines of best fit when plotting data
- determine uncertainty of the gradient and intercepts using minimum and maximum lines of best fit.

At times, even the motion of an object travelling in a straight line can be complicated. The object may travel forwards or backwards, speed up or slow down, or even stop. This information can be presented in graphical form.

The main advantage of a graph compared with a table is that it allows the nature of the motion to be seen clearly. Information that is contained in a table is not as readily accessible or as easy to interpret as information presented graphically. This module examines position–time, velocity–time and acceleration–time graphs.

POSITION-TIME (x-t) GRAPHS

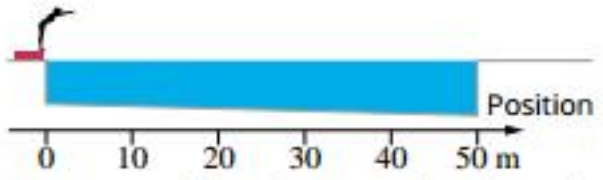


FIGURE 6.6.1 The swimmer stands at the end of a 50 m swimming pool.

A position–time graph indicates the position, x, of an object at any time, t, for motion that occurs over an extended time interval. However, the graph can also provide additional information.

Consider Sophie, shown in Figure 6.6.1, as she swims laps in a 50 m pool. Her position–time data are shown in Table 6.6.1. The starting point is treated as the origin for this motion.

TABLE 6.6.1 Positions and times of a swimmer completing 1.5 lengths of a pool

Time (s)	0	5	10	15	20	25	30	35	40	45	50	55	60
Position (m)	0	10	20	30	40	50	50	50	45	40	35	30	25

Analysis of Table 6.6.1 reveals several features of Sophie's swim.

- For the first 25 s, she swims at a constant rate. Every 5 s she travels 10 m in a positive direction, that is, her velocity is $+2\,\text{m s}^{-1}$.
- From 25 s to 35 s, her position does not change. She seems to be resting, as she is stationary for this 10 s interval.
- From 35 s to 60 s, she swims back towards the starting point, in a negative direction. On this return lap, she maintains a more leisurely rate of 5 m every 5 s, so her velocity is $-1\,\text{m s}^{-1}$. However, Sophie does not complete this lap but ends 25 m from the start.

This data is shown more conveniently on the position–time graph in Figure 6.6.2.

The displacement, s, of the swimmer can be determined by comparing the initial and final positions. For example, her displacement between 20 s and 60 s is:

$$\begin{aligned} s &= \Delta x \\ &= \text{final position} - \text{initial position} \\ &= 25 - 40 \\ &= -15\,\text{m} \end{aligned}$$

You can see from the graph in Figure 6.6.2 that the swimmer has a displacement of +50 m during the first 25 s. Her average velocity is $+2\,m\,s^{-1}$ or $2\,m\,s^{-1}$ to the right during the first 25 s. You can obtain this value by finding the gradient of this section of the graph.

$$\text{gradient} = \frac{\text{rise}}{\text{run}} = \frac{50-0}{25-0} = 2\,m\,s^{-1}$$

A positive velocity indicates that the object is moving in a positive direction and negative velocity indicates motion in a negative direction, as would be found when taking a gradient from 35 s to 60 s in Figure 6.6.2.

To confirm that the gradient of a position–time graph is a measure of velocity you can use **dimensional analysis** (the process of ensuring equations make sense by checking the units on both sides match):

$$\text{gradient of } x\text{–}t \text{ graph} = \frac{\text{rise}}{\text{run}} = \frac{\Delta x\,(\text{m})}{\Delta t\,(\text{s})} = v\,(\text{m s}^{-1})$$

The units of this gradient will be metres per second ($m\,s^{-1}$) so gradient is a measure of velocity. Note that the rise in the graph is the change in position, which is the definition of displacement $\Delta x = s$.

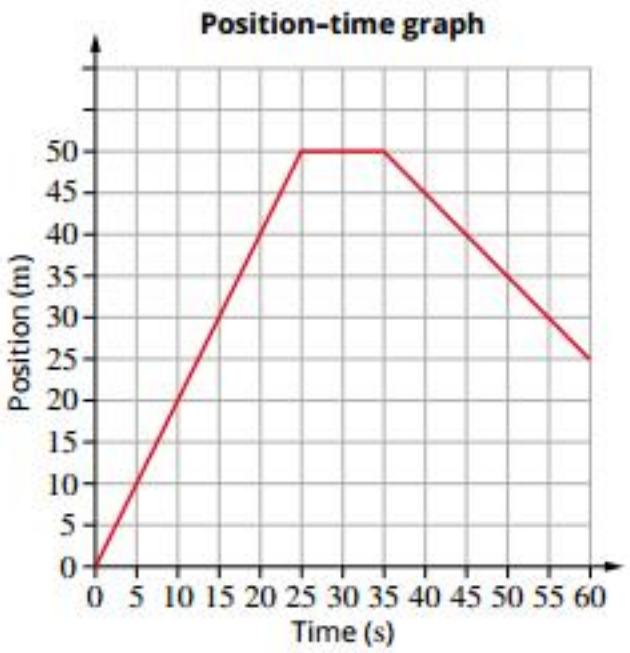
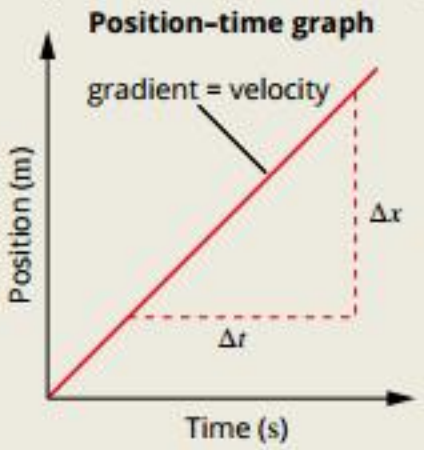


FIGURE 6.6.2 This position–time graph represents the motion of a swimmer travelling 50 m along a pool, then resting and swimming back towards the starting position. The swimmer finishes halfway along the pool.

Velocity, v, is given by the gradient of a position–time graph.



Position–time graph with gradient. Note that the change in position, Δx, is the same as the displacement, s.

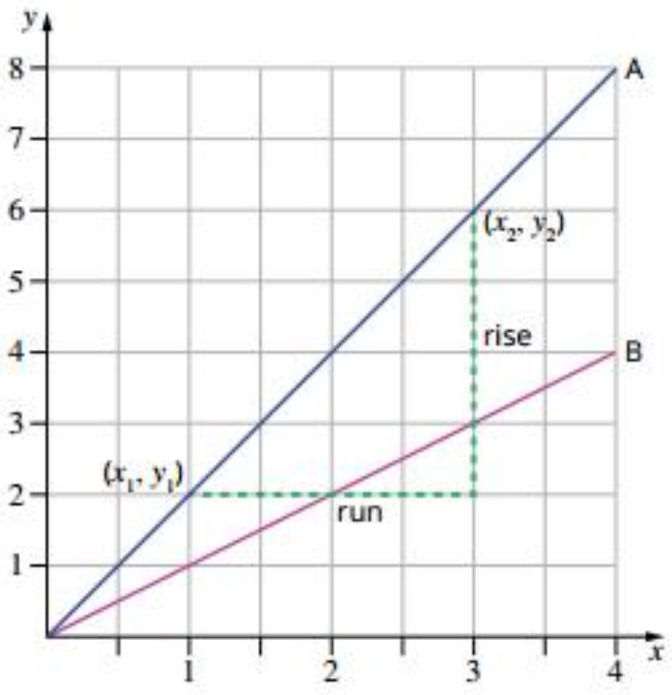
SKILLBUILDER

Interpreting the slope of a linear graph

Scientists often represent a relationship between two variables as a graph. For directly proportional relationships, the variables are connected by a straight line that passes through the origin, where the slope (or gradient) of the line represents the constant of proportionality between the two variables.

The slope or gradient of the line is defined as the ratio of change between two points in the vertical axis (rise) $y_2 - y_1$, divided by the change between two points in the horizontal axis (run) $x_2 - x_1$. In other words, it measures the rate at which one variable (the dependent variable) changes with respect to the other (the independent variable): gradient = $\frac{y_2 - y_1}{x_2 - x_1}$.

The graph shown has two straight lines with different slopes. The steeper slope (blue line, A) indicates that the rate of change is faster. This means the change is happening more quickly. The flatter slope (pink line, B) indicates that the rate of change is slower. This means the change is happening more slowly.



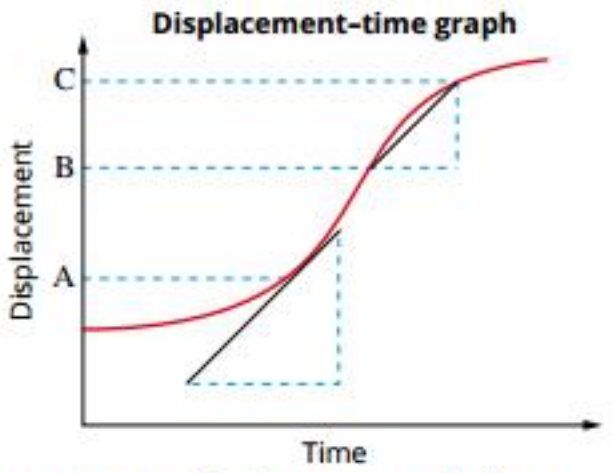


FIGURE 6.6.3 The instantaneous velocity at point A is the gradient of the tangent at that point. The average velocity between points B and C is the gradient of the chord between these points on the graph.

Non-uniform velocity

For motion with uniform (constant) velocity, the position–time graph will be a straight line, but if the velocity is non-uniform, the graph will be curved.

If the position–time graph is curved:

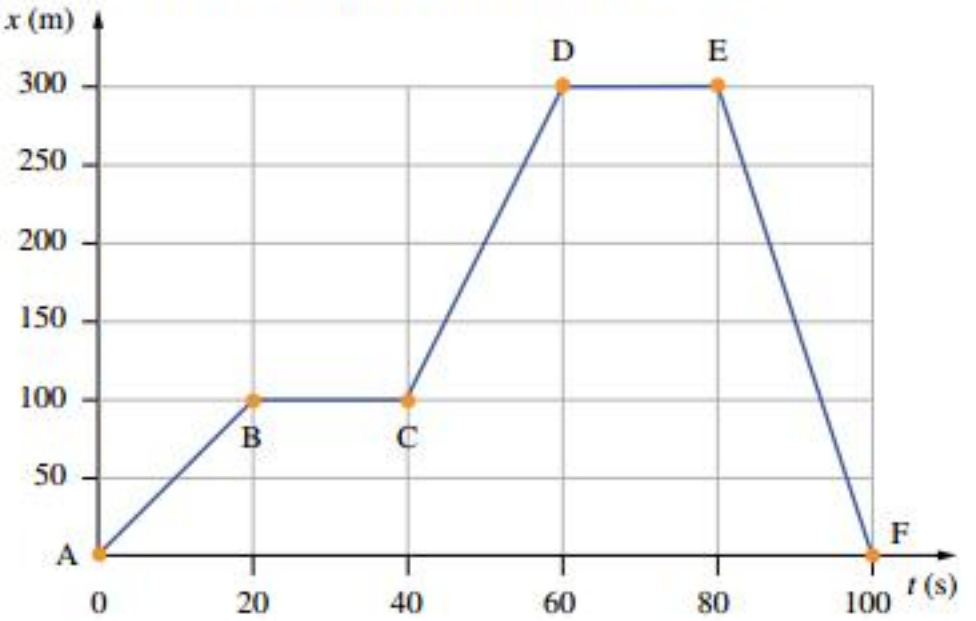
- the instantaneous velocity will be the gradient of the tangent to the line at that point.
- the average velocity will be the gradient of the chord between two points.

This is illustrated in Figure 6.6.3.

Worked example 6.6.1

ANALYSING A POSITION–TIME GRAPH

The motion of a cyclist is represented by the position–time graph below, with important features of the motion labelled A, B, C, D, E and F.



a Calculate the velocity of the cyclist between A and B.

Thinking	Working
Determine the change in position (displacement) of the cyclist between A and B using: s = final position – initial position	At A, $x = 0\,\text{m}$ At B, $x = 100\,\text{m}$ $s = 100 - 0$ $= +100\,\text{m}$ or $100\,\text{m}$ forwards (that is, away from the starting point)
Determine the time taken to travel from A to B.	$\Delta t = 20 - 0 = 20\,\text{s}$
Calculate the gradient of the graph between A and B using: gradient of x–t graph $= \frac{\text{rise}}{\text{run}} = \frac{\Delta x}{\Delta t}$ Remember that $\Delta x = s$.	gradient $= \frac{100}{20}$ $= 5$
State the velocity, using: gradient of x–t graph = velocity Use the sign convention to state the answer with its direction.	The gradient is 5, so the velocity is $+5\,\text{m s}^{-1}$ or $5\,\text{m s}^{-1}$ forwards.

b Describe the motion of the cyclist between B and C.	
Thinking	**Working**
Interpret the shape of the graph between B and C.	The graph is flat between B and C, indicating that the cyclist's position is not changing for this time. So, the cyclist is not moving. If the cyclist is not moving, the velocity is $0\,m\,s^{-1}$.
Confirm the result by calculating the gradient between B and C using: gradient of x–t graph $= \frac{\text{rise}}{\text{run}} = \frac{\Delta x}{\Delta t}$ Remember that $\Delta x = s$.	gradient $= \frac{0}{20}$ $= 0$

➤ Try yourself 6.6.1

ANALYSING A POSITION–TIME GRAPH

Use the graph shown in Worked example 6.6.1 to answer the following questions.

a Calculate the velocity of the cyclist between E and F.

b Describe the motion of the cyclist between D and E.

VELOCITY–TIME (v–t) GRAPHS

A graph of velocity, v, against time, t, shows how the velocity of an object changes with time. This type of graph is useful for analysing the motion of an object moving in a complex manner.

Analysing motion

Consider the example of the girl in Figure 6.6.4. Aliyah is running back and forth along an aisle in a supermarket. A study of the velocity–time graph in Figure 6.6.4 shows that Aliyah has a positive velocity (runs in a positive direction) for the first 6 s. Between 6 s and 7 s she is stationary, and then for the final 3 s she has a negative velocity (runs in the opposite direction).

The graph in Figure 6.6.4 shows Aliyah's velocity at each instant in time.

- For the first 4 s, she moves in a positive direction with a constant speed of $3\,m\,s^{-1}$.
- From 4 s to 6 s, she continues moving in a positive direction but slows down.
- At 6 s, she comes to a stop for 1 second.
- For the final 3 s, she accelerates in the negative direction for 1 s then travels at a constant velocity of $-1\,m\,s^{-1}$ for 1 s. She then slows down and comes to a stop at 10 s.

Remember that whenever the graph is below the time axis, velocity is negative, which indicates travel in the opposite direction. So, she is travelling in the opposite direction for the last 3 s of her journey.

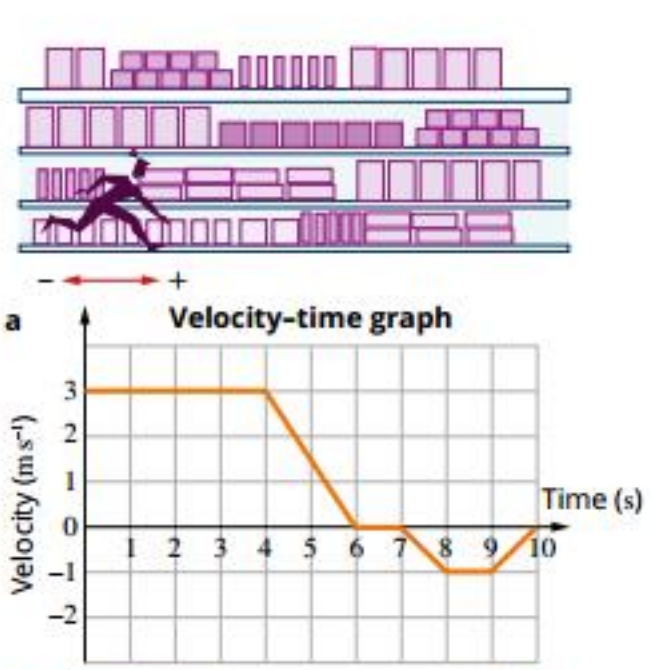


FIGURE 6.6.4 Diagram and v–t graph for Aliyah running along an aisle.

Finding displacement

A velocity–time graph can also be used to find the displacement of an object.

It is easier to see why the area under the v–t graph gives the displacement when velocity is constant. For example, the graph in Figure 6.6.5 shows that in the first 4 s of motion, Aliyah moves with a constant velocity of $+3\,m\,s^{-1}$. Note that the area under the graph for this period of time is a rectangle. Her displacement, s, during this time can be determined by rearranging the formula for velocity:

$$v = \frac{s}{\Delta t}$$
$$\therefore s = v \times \Delta t$$
$$= \text{height} \times \text{base}$$
$$= \text{area under } v\text{-}t \text{ graph}$$

Aliyah then slows from $3\,m\,s^{-1}$ to zero in the next 2 s. To understand why the triangular area under the graph gives the displacement for this period, you would need more complicated mathematics, known as calculus, which is beyond the scope of this book.

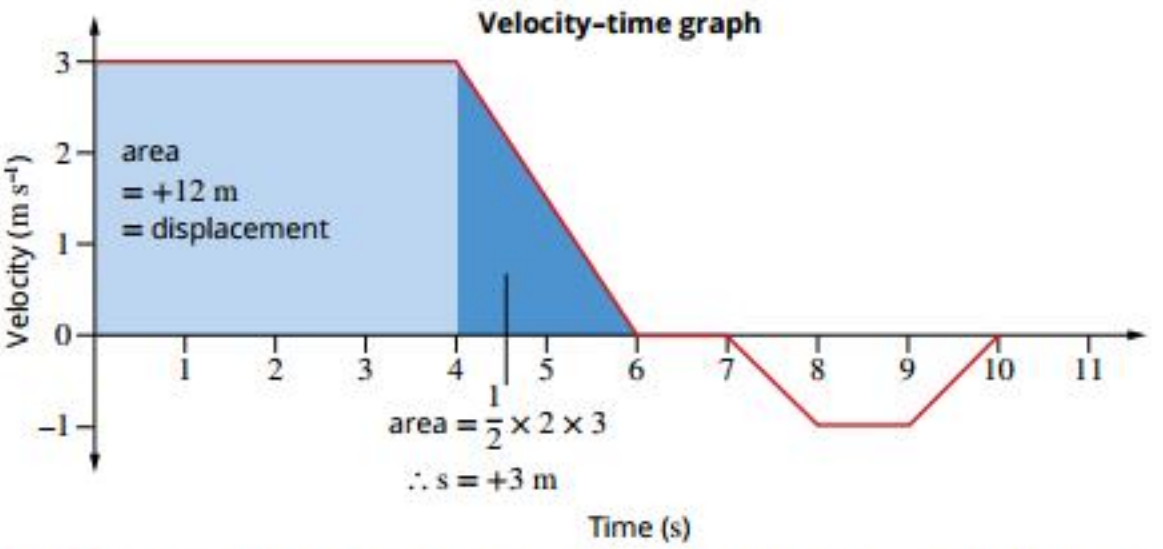


FIGURE 6.6.5 Displacement values shown have been determined from the area between the *v*–*t* curve and the time axis.

The area under the graph in Figure 6.6.5 can be used to find Aliyah's displacement.

For the first 4 s:

$$\text{Area} = l \times w$$
$$= 3 \times 4$$
$$= +12\,m$$

From 4 s to 6 s:

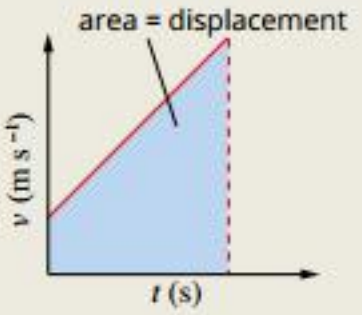
$$\text{Area} = \frac{b \times h}{2}$$
$$= \frac{2 \times 3}{2}$$
$$= +3\,m$$

The total displacement during the first 6 s

$$= +12\,m + 3\,m = +15\,m$$

Displacement, *s*, is given by the area under a velocity–time graph. This is the area between the graph and the time axis.

- **An area above the time axis indicates a positive displacement and motion in a positive direction.**
- **An area below the time axis indicates a negative displacement and motion in a negative direction.**

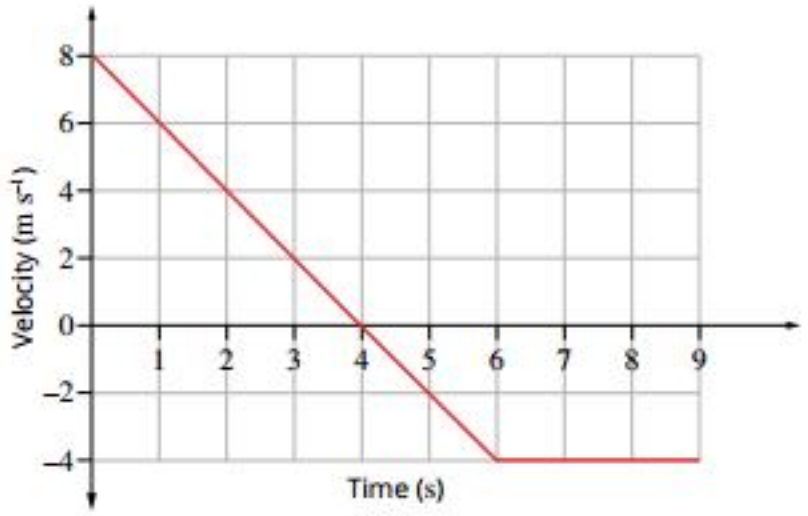


The area under a *v*–*t* graph gives displacement.

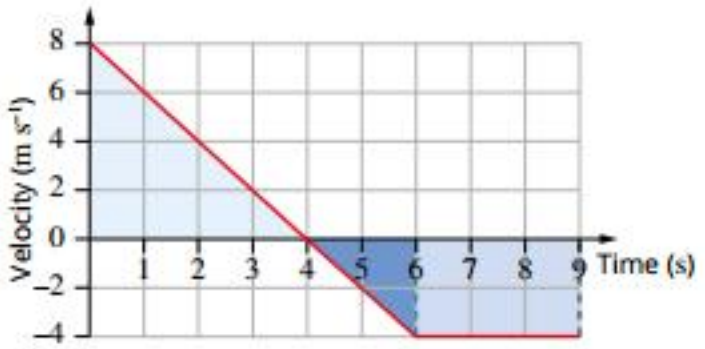
Worked example 6.6.2

ANALYSING A VELOCITY–TIME GRAPH

The motion of a radio-controlled car initially travelling east in a straight line across a driveway is represented by the graph below.



a Calculate the displacement of the car during the first 4 seconds.

Thinking	Working
Displacement is the area under the graph. So, calculate the area under the graph for the time for which you want to find the displacement. Use displacement = $b \times h$ for squares and rectangles. Use displacement = $\frac{1}{2}(b \times h)$ for triangles.	 The area from 0 to 4 s is a triangle, so: area = $\frac{1}{2}(b \times h)$ = $\frac{1}{2} \times 4 \times 8$ = +16 m
Use the sign convention to state the answer with its direction.	Displacement = 16 m east

b Determine the average velocity of the car for the first 4 seconds.

Thinking	Working
Identify the equation and variables and apply the sign convention.	$v = \frac{s}{\Delta t}$ $s = +16$ m $\Delta t = 4$ s
Substitute values into the equation: $v = \frac{s}{\Delta t}$	$v = \frac{s}{\Delta t}$ $= \frac{+16}{4}$ $= +4$ m s^{-1}
Use the sign convention to state the answer with its direction.	$v_{av} = 4$ m s^{-1} east

➤ Try yourself 6.6.2

ANALYSING A VELOCITY–TIME GRAPH

Use the graph shown in Worked example 6.6.2 to answer the following questions.

a Calculate is the displacement of the car from 4 to 6 seconds.

b Determine the average velocity of the car from 4 to 6 seconds.

Acceleration from a velocity–time (v–t) graph

The acceleration of an object can also be found from a velocity–time graph, as shown in Figure 6.6.6.

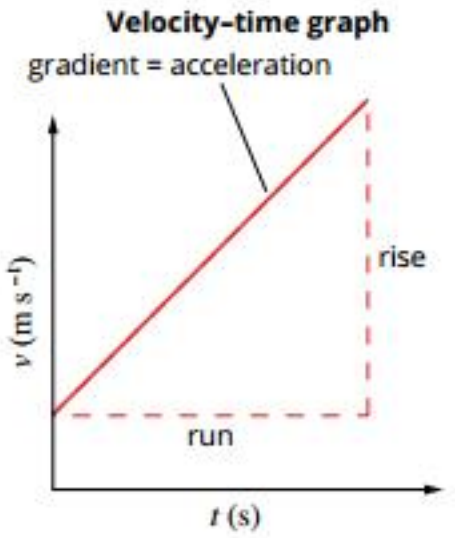


FIGURE 6.6.6 Gradient as displayed in a v–t graph

$$\text{gradient of } v\text{–}t \text{ graph} = \frac{\text{rise}}{\text{run}} = \frac{\Delta v\ (\text{m s}^{-1})}{\Delta t\ (\text{s})} = a\ (\text{m s}^{-2})$$

Consider the motion of Aliyah in the supermarket. Figure 6.6.7 shows Aliyah's velocity at each instant in time. Acceleration is the change in velocity divided by the time taken, so acceleration can be calculated using the gradient of the v–t graph. Aliyah's acceleration for the first 6 seconds is calculated as follows.

- For the first 4 seconds, the line is horizontal, so she is moving at a constant speed of $3\,\text{m s}^{-1}$. Her acceleration is $0\,\text{m s}^{-2}$.
- From 4 to 6 seconds, she is moving in a positive direction but is slowing down from $3\,\text{m s}^{-1}$ to rest. Her acceleration is:

$$a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t} = \frac{0 - 3}{2} = -1.5\,\text{m s}^{-2}$$

- The negative sign means that the acceleration is in the opposite direction.

The gradient of a velocity–time graph gives the average acceleration of the object over the time interval.

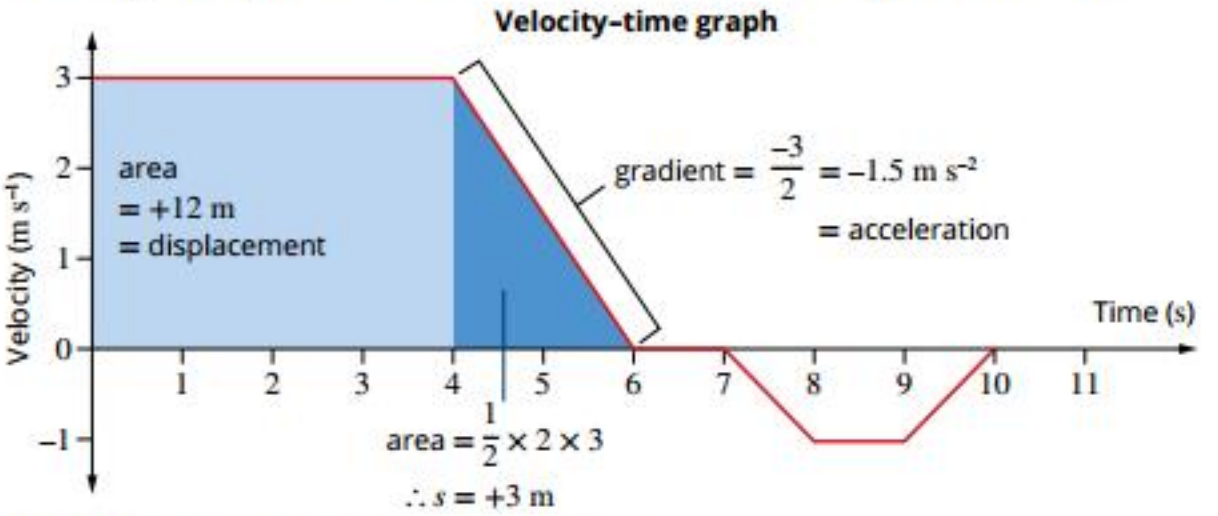
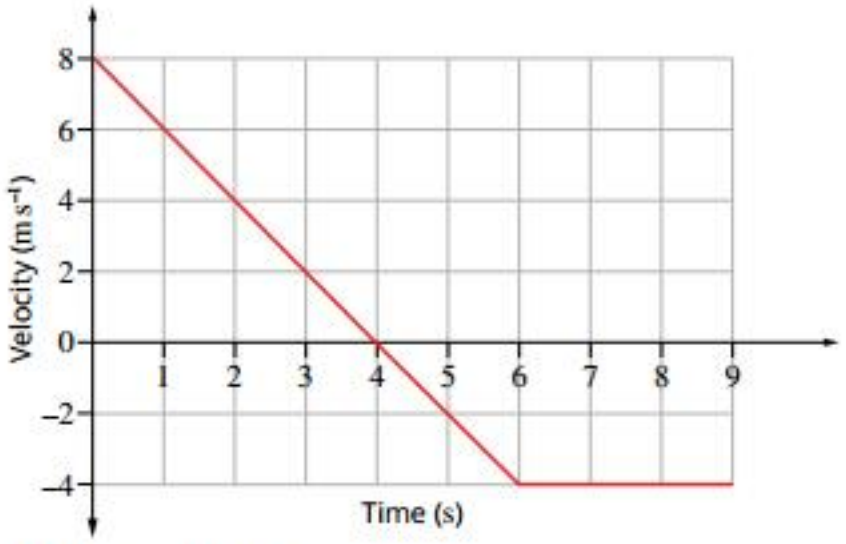


FIGURE 6.6.7 Acceleration as displayed in a v–t graph

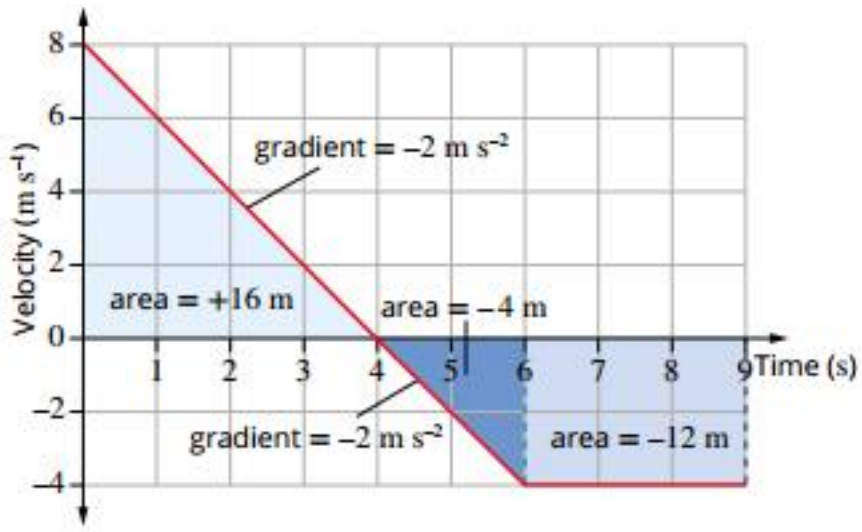
Worked example 6.6.3

ACCELERATION FROM A VELOCITY–TIME GRAPH

Consider the motion of the radio-controlled car in Worked example 6.6.2, which is initially travelling east in a straight line across a driveway, as shown by the graph below.



Calculate the acceleration of the car during the first 4 s.

Thinking	Working
Acceleration is the gradient of a *v*–*t* graph. Calculate the gradient from time 0 s to 4 s using: Gradient = $\frac{\text{rise}}{\text{run}}$	 Gradient = $\frac{\text{rise}}{\text{run}}$ = $\frac{-8}{4}$ = −2 m s^{-2}
Use the sign convention to state the answer with its direction. Note: In this case, although the acceleration is in the westerly direction, the car is still moving in the easterly direction but slowing down.	acceleration = −2 m s^{-2} east (or 2 m s^{-2} west)

➤ Try yourself 6.6.3

ACCELERATION FROM A VELOCITY–TIME GRAPH

For the graph shown in Worked example 6.6.3, calculate the acceleration of the car during the period from 4 to 6 seconds.

Distance travelled

A velocity–time graph can also be used to calculate the distance travelled. The process of determining distance requires you to calculate the area under the v–t graph, in the same way as when calculating displacement. However, because the distance travelled by an object always increases as the object moves, regardless of direction, you must add up all the areas between the graph and the time axis, regardless of whether the area is above or below the axis.

For example, Figure 6.6.8 shows the velocity–time graph of the radio-controlled car from Worked example 6.6.3. The area above the time axis, which corresponds to motion in the positive direction, is +16 m. The areas below the axis, which correspond to negative motion, are −4 m and −12 m.

To calculate the total displacement, add up each displacement:

Total displacement

$= 16 + (-4) + (-12)$

$= 16 - 16$

$= 0\,\text{m}$

To calculate the total distance, add up the magnitude of the areas, and ignore the signs:

Total distance

$= 16 + 4 + 12$

$= 32\,\text{m}$

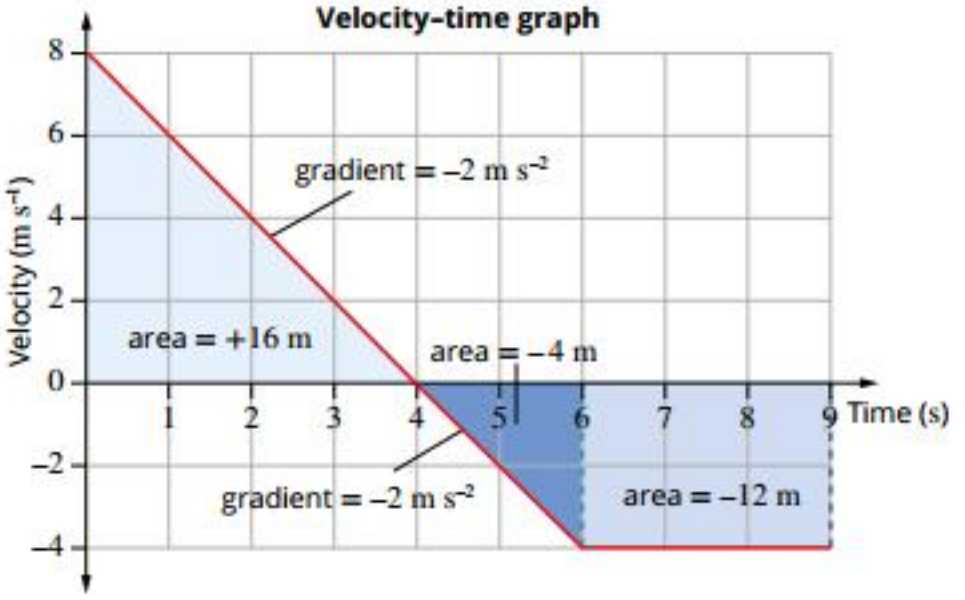


FIGURE 6.6.8 Both distance and displacement can be calculated by using the areas under the velocity–time graph.

Non-uniform acceleration

For motion with uniform (constant) acceleration, the velocity–time graph will be a straight line. For non-uniform acceleration, the velocity–time graph will be curved. If the velocity–time graph is curved:

- the instantaneous acceleration is the gradient of the tangent to the line at that point
- the average acceleration will be the gradient of the chord between two points.

The displacement can still be calculated by finding the area under the graph; however, you will need to make some estimations. Using calculus, the instantaneous acceleration would be determined using differentiation and the displacement using integration or antidifferentiation.

ACCELERATION–TIME (a–t) GRAPHS

An acceleration–time graph simply indicates the acceleration of the object as a function of time. The area under an acceleration–time graph is found by multiplying an acceleration, a, and a period of time, Δt, value. The area gives a change in velocity, Δv, value:

$$\text{area} = a \times \Delta t = \Delta v$$

To establish the actual velocity of the object, its initial velocity must be known. Figure 6.6.9 shows both Aliyah's velocity versus time (v–t) and acceleration versus time (a–t) graphs.

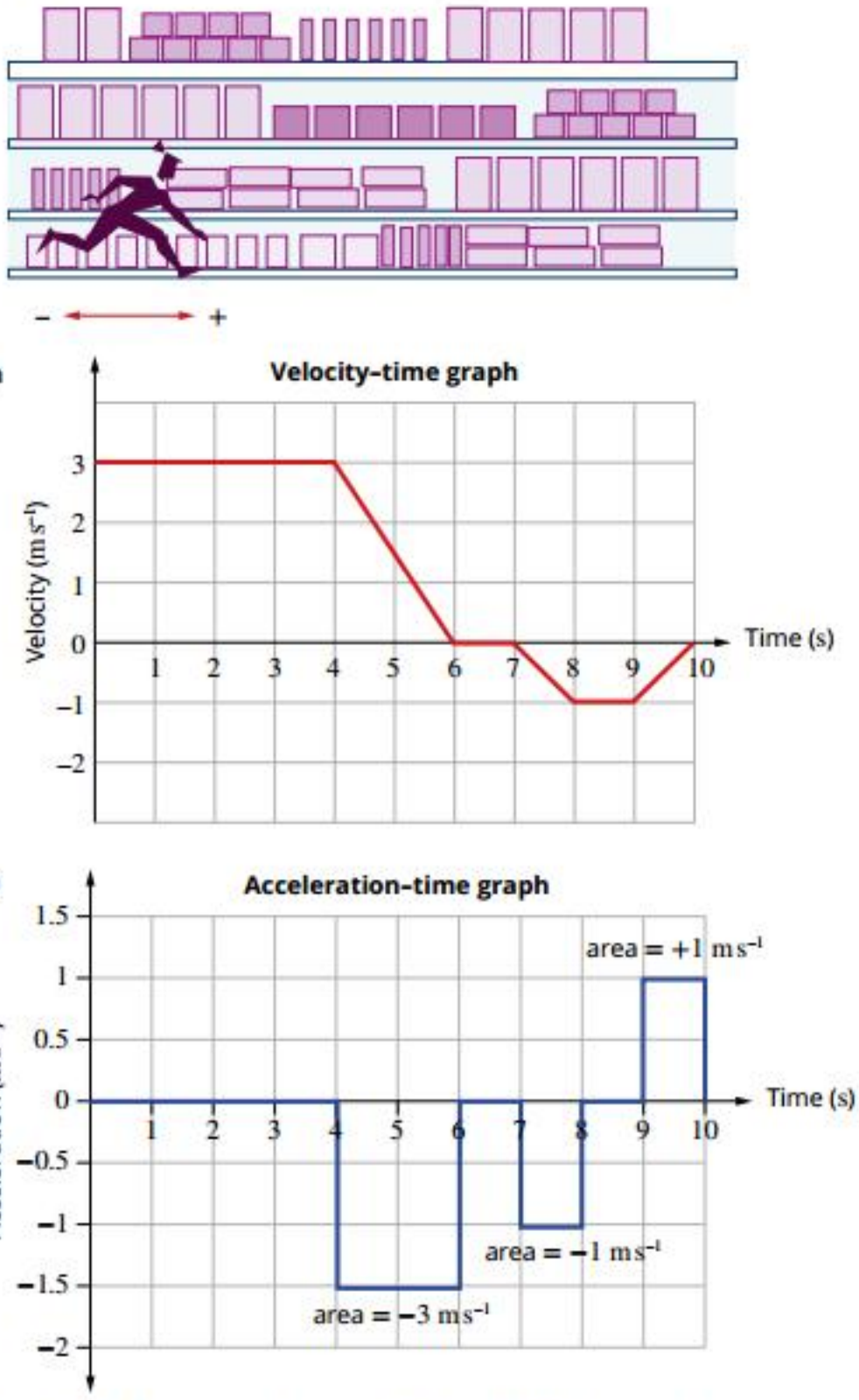


FIGURE 6.6.9 (a) Aliyah's velocity versus time (v–t) graph. (b) Aliyah's acceleration versus time (a–t) graph. The area under the v–t graph gives the value for acceleration, a.

From 0 to 4 s the velocity is constant, so the gradient, and hence the acceleration, is zero. The area under the curve from 4 to 6 s shows a Δv of $-3\,\text{m s}^{-1}$. This indicates that Aliyah has slowed down by $3\,\text{m s}^{-1}$ during this time. The $v-t$ graph confirms this. Her initial speed is $3\,\text{m s}^{-1}$, so she must be stationary ($v = 0$) after 6 s. The v–t graph confirms this.

This calculation could not be made without knowing Aliyah's initial velocity.

UNCERTAINTIES USING MINIMUM AND MAXIMUM LINES OF BEST FIT

There are several factors that can influence the precision and accuracy of your experimental data. Limitations include the measurement devices—such as rulers that only measure to 1 cm intervals, or timers that only measure to the closest millisecond—or human error, such as reaction times. Much of this is covered in Chapter 1 of the eBook.

Minimum and maximum lines of best fit address uncertainty in gradients and intercepts by finding the difference between the two lines of best fit and dividing this difference by two. Unlike error bars—which look at the error of a single data point—the minimum and maximum lines of best fit look at the error in the trend across the entire set of collected data.

The line of best fit with the lowest gradient is the minimum line of best fit. The line of best fit with the steepest gradient is the maximum line of best fit. Figure 6.6.10 shows a graph with vertical error bars and a minimum line of best fit (green, A) and maximum line of best fit (orange, B).

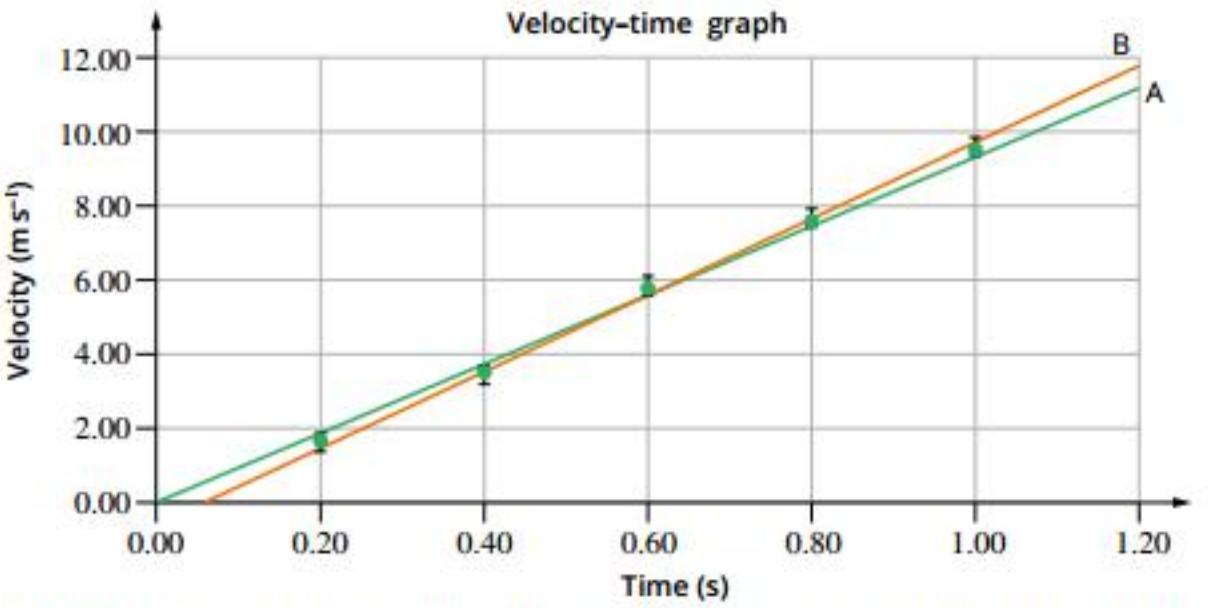


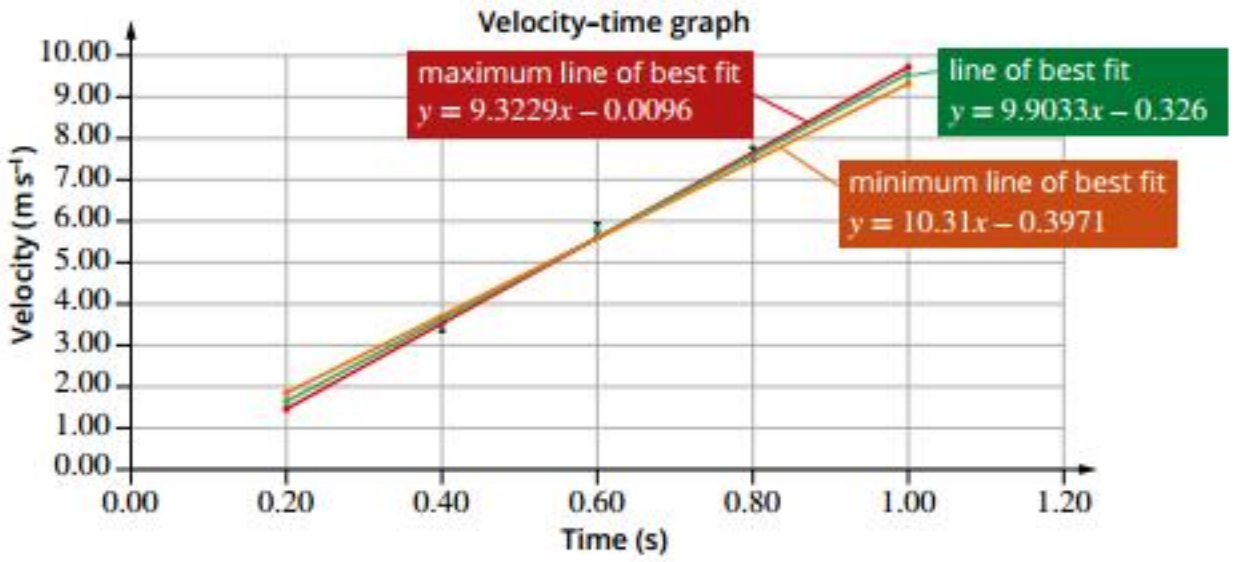
FIGURE 6.6.10 A graph for velocity–time featuring error bars as well as a minimum line of best fit (green) and a maximum line of best fit (orange).

Worked example 6.6.4

FINDING UNCERTAINTY AND MINIMUM AND MAXIMUM LINES OF BEST FIT FROM EXPERIMENTAL DATA

A group of students drop a basketball from a 2 m height and use a motion detector to find the velocity over time as the basketball falls to the ground. They use these measurements to estimate acceleration due to gravity. They conduct three trials for each drop and record the velocity at 0.2 s intervals. They record their results in a table and use the data to draw a graph with vertical error bars, line of best fit and minimum and maximum lines of best fit, as shown.

	Velocity ($m\,s^{-1}$)				
Time (s)	**Trial 1**	**Trial 2**	**Trial 3**	**Average**	**Absolute uncertainty**
0.20	1.45	1.84	1.69	1.66	0.20
0.40	3.32	3.67	3.55	3.51	0.18
0.60	5.60	5.92	5.82	5.78	0.16
0.80	7.42	7.74	7.68	7.61	0.16
1.00	9.32	9.72	9.50	9.51	0.20



a Use the gradient to estimate the acceleration due to gravity.

Thinking	Working
Identify how acceleration can be determined from the gradient.	As the x-axis is time (s) and the y-axis is velocity ($m s^{-1}$), the gradient of the v–t graph will be: $\frac{\text{rise}}{\text{run}} = \frac{\Delta v\ (m s^{-1})}{\Delta t\ (s)} = a\ (m s^{-2})$ This means the gradient of the v–t graph will be the ball's acceleration. Another method is to use the formula for linear relationships, $y = mx + c$. The v–t graph follows the formula $v = u + at$, where u is the y-intercept and a is the gradient, also demonstrating that the gradient of the v–t graph will be the ball's acceleration.
Determine the gradient from the line of best fit.	From the line of best fit, you can see the gradient is $9.90 m s^{-2}$.
State the estimated acceleration due to gravity.	From the gradient, acceleration due to gravity could be estimated as $9.90 m s^{-2}$.

b Use the minimum and maximum lines of best fit to find the uncertainty of the gradient.

Thinking	Working
Substitute the gradient of the minimum and maximum lines into the equation.	uncertainty in the gradient $= \frac{\text{maximum gradient} - \text{minimum gradient}}{2}$ $= \frac{10.31 - 9.32}{2}$ $= 0.494$
State the uncertainty in the gradient.	The uncertainty in the gradient is $\pm 0.494 m s^{-2}$. $= \pm 0.49 m s^{-2}$.

c Use the minimum and maximum lines of best fit to find the uncertainty of the y-intercept.

Thinking	Working
Substitute the y-intercept of the minimum and maximum lines into the equation.	uncertainty in the y-intercept $= \frac{\text{maximum } y\text{-intercept} - \text{minimum } y\text{-intercept}}{2}$ $= \frac{0.3971 - 0.0096}{2}$ $= 0.194$
State the uncertainty in the y-intercept.	The uncertainty in the y-intercept is ± 0.19 (to 2 decimal places) $m s^{-1}$.

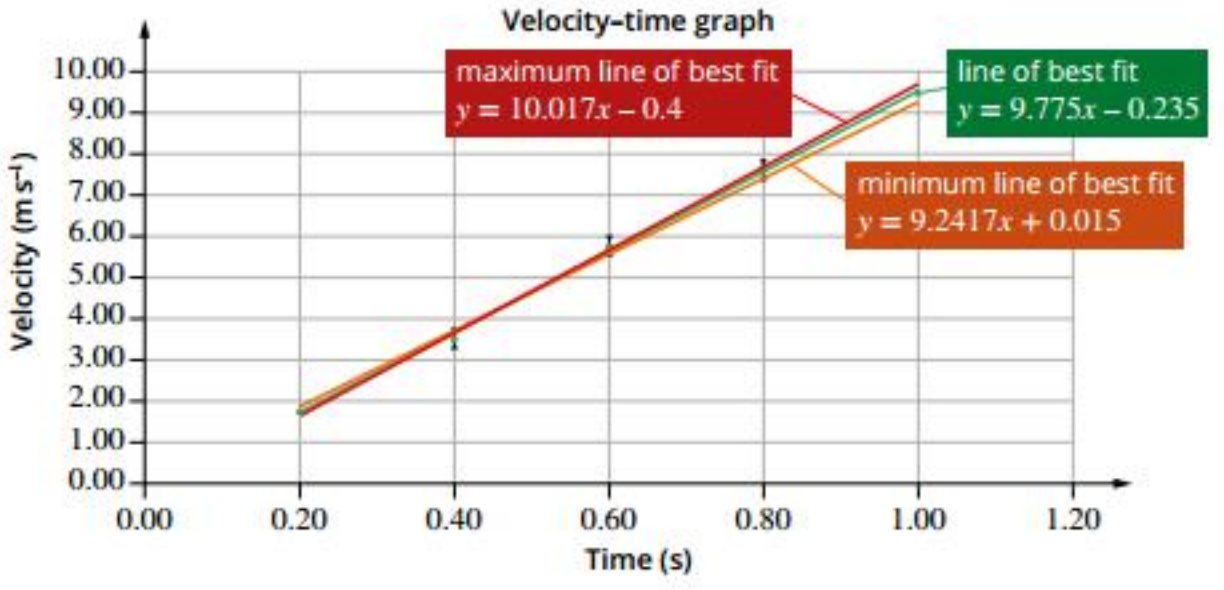
d Identify a mathematical relationship between the velocity of the ball and time, including the uncertainty of the gradient and *y*-intercept.	
Thinking	**Working**
Represent the equation for the line of best fit in terms of velocity and time.	The equation for the line of best fit is $y = 9.90x - 0.33$, where the *y*-axis is velocity, and the *x*-axis is time. The relationship between the velocity of the ball (v) and time (t) is $v = 9.90t - 0.33$.
Write the relationship to include uncertainty of the gradient and *y*-intercept.	$v = (9.90 \pm 0.49)t - 0.33 \pm 0.19$

➤ Try yourself 6.6.4

FINDING UNCERTAINTY AND MINIMUM AND MAXIMUM LINES OF BEST FIT FROM EXPERIMENTAL DATA

A group of students drop a tennis ball from a 2 m height and use a motion detector to find the velocity over time as the tennis ball falls to the ground. They use these measurements to estimate acceleration due to gravity. They conduct three trials for each drop and record the velocity at 0.2 s intervals. They record their results in a table and use the data to draw a graph with vertical error bars, line of best fit and minimum and maximum lines of best fit, as shown below.

	Velocity ($m s^{-1}$)				
Time (s)	**Trial 1**	**Trial 2**	**Trial 3**	**Average**	**Absolute uncertainty**
0.20	1.67	1.87	1.75	1.76	0.10
0.40	3.22	3.65	3.62	3.50	0.22
0.60	5.55	6.02	5.78	5.78	0.24
0.80	7.41	7.82	7.69	7.64	0.21
1.00	9.23	9.65	9.52	9.47	0.21



a Use the gradient to estimate the acceleration due to gravity.

b Use the minimum and maximum lines of best fit to find the uncertainty of the gradient.

c Use the minimum and maximum lines of best fit to find the uncertainty of the *y*-intercept.

d Identify a mathematical relationship between the velocity of the ball and time, including the uncertainty of the gradient and *y*-intercept.

6.6 Review

SUMMARY

- A position–time graph can be used to determine the location of an object at any given time. Additional information can also be derived from the graph:
  - Displacement is given by the change in position of an object.
  - The velocity of an object is given by the gradient of the position–time graph.
  - If the position–time graph is curved, the gradient of the tangent at a point gives the instantaneous velocity. The gradient of a chord between two points gives the average velocity between those points.
- The gradient of a velocity–time graph is the acceleration of the object.
- The area under a velocity–time graph is the change in displacement of the object.
- The area under an acceleration–time graph is the change in velocity of the object.
- Vertical error bars on graphs can be used to demonstrate uncertainty in the dependent variable of experimental data.
- Minimum and maximum lines of best fit can be used to model uncertainty in the gradient and intercepts of experimental data.

KEY QUESTIONS

Describe

1 State the meaning of the following features of a graph.
- **a** The gradient of a position–time graph.
- **b** The gradient of a velocity–time graph.
- **c** The area under a velocity–time graph.
- **d** The area under an acceleration–time graph.

2 Recall how to determine the direction of an object's velocity from the gradient of a position–time graph.

3 Recall how to determine the direction of an object's displacement from the area of a velocity–time graph.

Apply

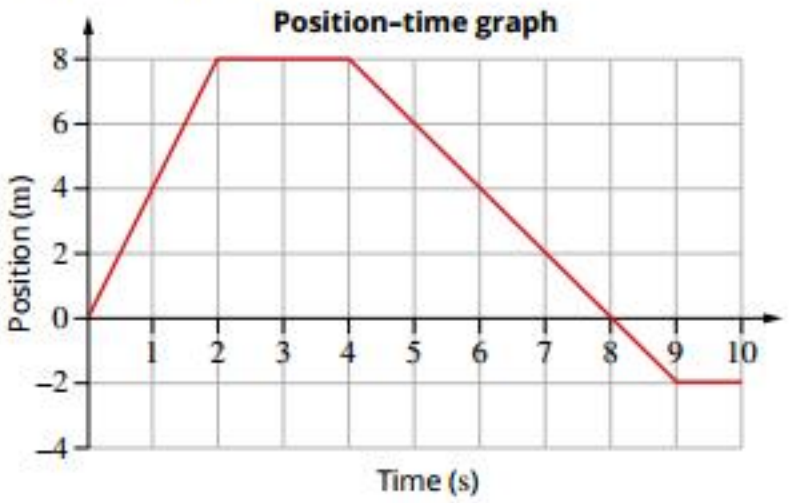
4 Draw a velocity–time graph for a tennis ball hit vertically up into the air that takes 5 seconds to land. The initial velocity of the ball is $+24.5\ m s^{-1}$. It is momentarily at rest at 2.5 seconds before returning to the racket at a velocity of $-24.5\ m s^{-1}$.

5 Interpret the graph from the previous question to determine at what point in the ball's flight it experienced negative acceleration.

Analyse

*The following information relates to questions **6–10**.*

The graph represents the straight-line motion of a radio-controlled toy car.



6 Describe the motion of the car in terms of its position.

7 Determine the position of the toy car at the following times.
- **a** 2.0 s
- **b** 4.0 s
- **c** 6.0 s
- **d** 10.0 s

8 Determine the time at which the car returned to its starting point.

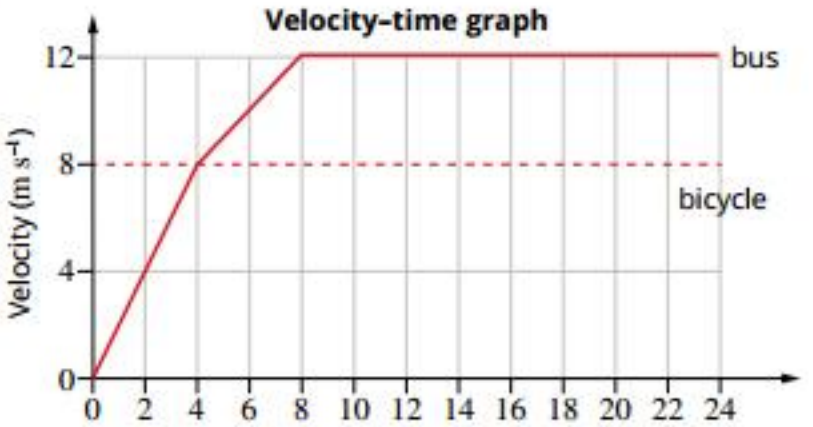
6.6 Review *continued*

9 Calculate the velocity of the toy car:
- **a** during the first 2.0s
- **b** at 3.0s
- **c** from 4.0s to 8.0s
- **d** at 8.0s
- **e** from 8.0s to 9.0s.

10 Calculate the following (in metres) for the car's 10.0s motion:
- **a** distance
- **b** displacement.

*The following information relates to questions **11** and **12**.*

The velocity–time graphs for a bus and a bicycle travelling along the same straight stretch of road are shown below. The bus is initially at rest and starts moving as the bicycle passes it.



11 **a** Calculate the magnitude of the initial acceleration of the bus.
- **b** Calculate the time at which the bus overtakes the bicycle.
- **c** Calculate how far the bicycle has travelled before the bus catches it.
- **d** Calculate the magnitude of the average velocity of the bus during the first 8s.

12 **a** Draw an acceleration–time graph for the motion of the bus.
- **b** Interpret your acceleration–time graph to determine the change in velocity of the bus over the first 8.0s.

Chapter review

06

KEY TERMS

acceleration
air resistance
centre of mass
collinear
dimension
dimensional analysis
direction conventions
displacement
distance travelled
free-fall
magnitude
newton
position
rectilinear
resultant
scalar
speed
units
vector
vector diagram
velocity
velocity (average)
velocity (instantaneous)

KEY QUESTIONS

Describe

1 Select the scalar quantities in the list below.
- **A** force
- **B** time
- **C** acceleration
- **D** mass

2 Select the vector quantities in the list below.
- **A** displacement
- **B** distance
- **C** volume
- **D** velocity

3 A car travels 15.0 m s^{-1} north and another travels 20.0 m s^{-1} south. State why a sign convention is used to describe vectors like these.

4 Recall which direction the vector representing the force due to gravity points.

5 Recall which direction the vector representing a friction force points.

6 Select which of the following features of motion graphs can be used to find displacement.
- **A** gradient of a position–time graph
- **B** gradient of a velocity–time graph
- **C** area under a velocity–time graph
- **D** area under an acceleration–time graph

Apply

7 A basketball is dropped by a player and is in free-fall as it falls towards the ground. Identify the force acting on the basketball as it falls.

8 Describe which point on the basketball in the previous question will be used to measure its motion.

9 Angus inadvertently drops an egg while baking a cake and the egg falls vertically towards the ground. Identify which one of the following statements correctly describes how the egg falls.
- **A** The egg's acceleration increases.
- **B** The egg's acceleration is constant.
- **C** The egg's velocity is constant.
- **D** The egg's acceleration decreases.

10 A car is moving in a positive direction. It approaches a red light and slows down. Identify which of the following statements correctly describes its acceleration and velocity as it slows down:
- **A** The car has positive acceleration and negative velocity.
- **B** The car has negative acceleration and positive velocity.
- **C** Both the velocity and acceleration of the car are positive.
- **D** Both the velocity and acceleration of the car are negative.

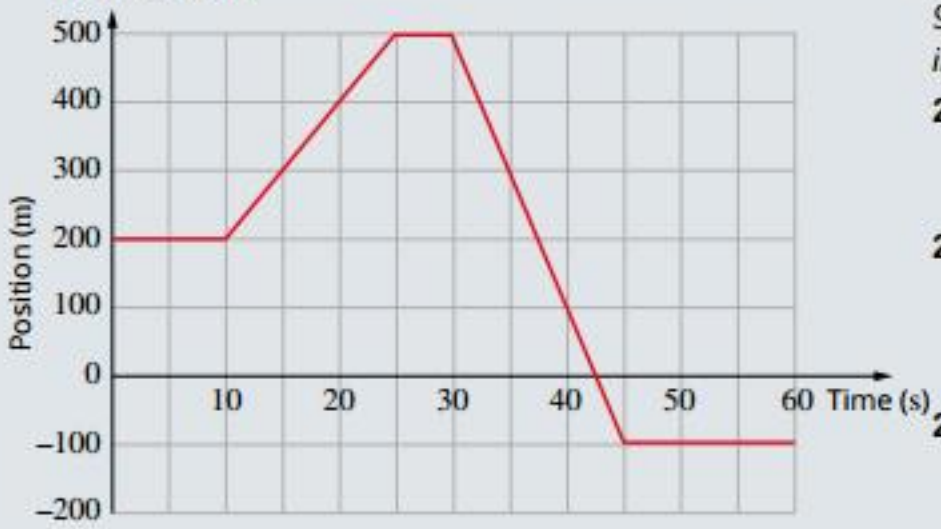
11 A basketballer applies a force with his hand to bounce the ball. Describe how a vector can be drawn to represent this situation.

12 The vector 20.0 N forwards is written as –20.0 N. Show how a vector representing 80.0 N backwards would be written.

13 A car travels at 95 km h^{-1} along a freeway. The acceleration due to gravity is 9.8 m s^{-2} down and air resistance is negligible. Calculate the speed of the car in m s^{-1}.

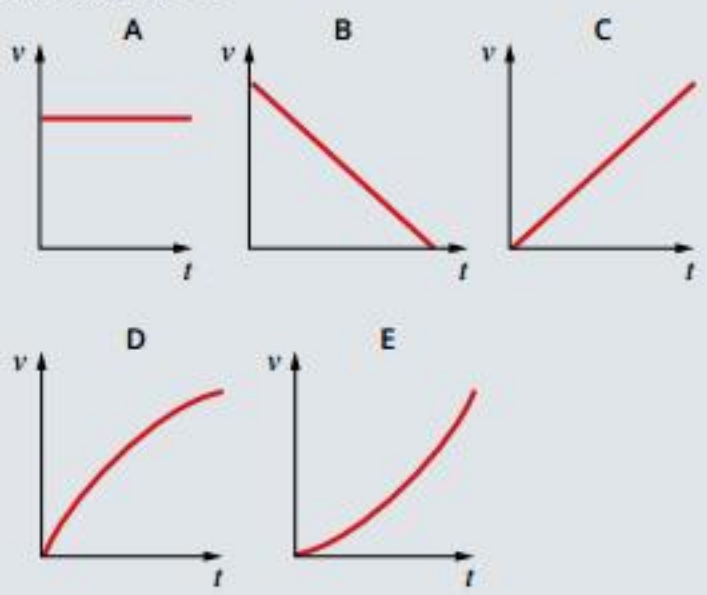
14 Draw a position–time graph for a dog that walks 20 m away from its owner in 3 seconds, stops for 2 seconds, then walks back to its owner over 5 seconds.

15 The position–time graph shows the position of a motorbike along a straight stretch of road as a function of time. The motorcyclist starts 200.0 m north of an intersection.



a Determine the time interval in which the motorcyclist is travelling in a northerly direction.
b Determine the time interval in which the motorcyclist is travelling in a southerly direction.
c Determine the time intervals in which the motorcyclist is stationary.
d Determine the time at which the motorcyclist is passing back through the intersection.

16 For each of the activities listed (**a–c**) indicate which of the following velocity–time graphs best represent the motion involved.



a A car slows down to a stop at a red light.
b A swimmer is travelling at a constant speed.
c A motorbike starts from rest with uniform acceleration.

Analyse

17 Determine the resultant vector of the following combination: 45.0 m forwards, 70.5 m backwards, 34.5 m forwards, 30.0 m backwards.

18 Determine the change in velocity of a bird that changes from flying 3.0 m s^{-1} to the right to flying 3.0 m s^{-1} to the left.

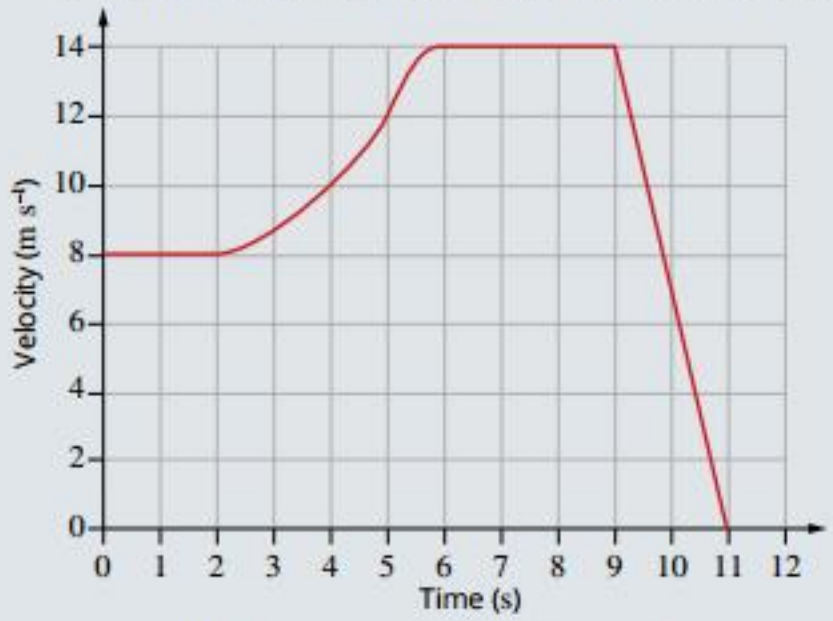
19 Determine the acceleration of a ball when its velocity changes from 5.0 m s^{-1} down to 4.5 m s^{-1} up over 3.0 ms.

*For questions **20–26**, the acceleration due to gravity is 9.8 m s^{-2} down and air resistance is negligible, unless indicated otherwise.*

20 A ping pong ball is falling vertically at 6.0 m s^{-1} as it hits the floor. It rebounds at 4.0 m s^{-1} up. Calculate its change in speed during the bounce.

21 A skier is travelling along a horizontal ski run at a speed of 15 m s^{-1}. The skier falls over and takes 2.5 s to come to rest. Calculate the average acceleration of the skier.

22 This velocity–time graph is for a road cyclist as he travels, initially north, along a straight section of track.



a Calculate the displacement of the cyclist during his journey.
b Calculate the magnitude of the average velocity of the cyclist during this 11.0 s interval. Give your answer correct to three significant figures.
c Calculate the acceleration of the cyclist at $t = 1$ s.
d Calculate the acceleration of the cyclist at $t = 10$ s.
e Determine which one or more of the following statements correctly describes the motion of the cyclist:
A He is always travelling north.
B He travels south during the final 2 s.
C He is stationary at $t = 8$ s.
D He returns to the starting point after 11 s.

23 A car starts from rest and has a constant acceleration of 3.5 m s^{-2} for 4.5 s. Calculate its final speed.

24 A jet-ski starts from rest and accelerates uniformly. If it travels 2.0 m in its first second of motion, calculate:
a the magnitude of its acceleration
b its speed at the end of the first second
c the distance the jet-ski travels in its second second of motion.

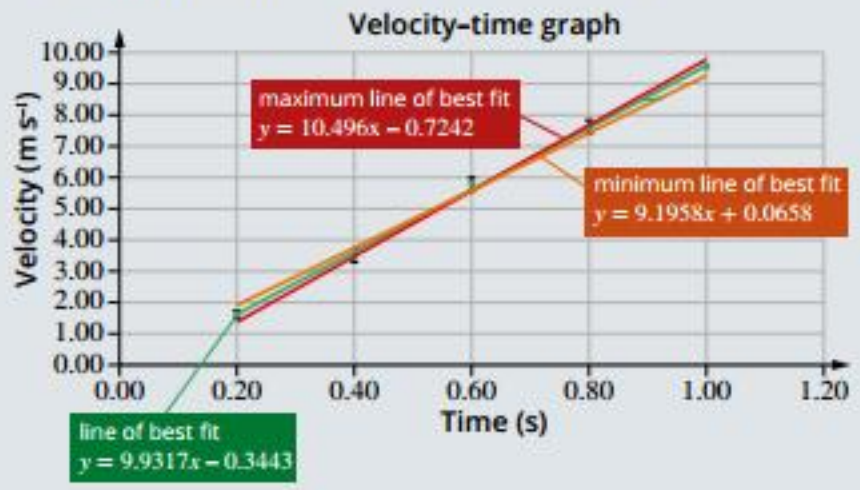
25 A skater is travelling along a horizontal skate rink at a speed of $10.0\,m\,s^{-1}$. The skater falls over and takes 10.0 m to come to rest.

- **a** Calculate average acceleration of the skater.
- **b** State the time it takes for the skater to come to a stop.

26 A cyclist, Anna, is travelling at a constant speed of $12\,m\,s^{-1}$ when she passes a stationary bus. The bus starts moving just as Anna passes, and it accelerates uniformly at $1.5\,m\,s^{-2}$.

- **a** Determine when the bus reaches the same speed as Anna.
- **b** Determine how long the bus takes to catch Anna.
- **c** Determine the distance Anna has travelled when the bus catches up with her.

*The following information relates to questions **27** and **28**.*
Students complete an investigation to model acceleration due to gravity. They create the following plot of their data with minimum and maximum lines of best fit.



27 Use the minimum and maximum lines of best fit to calculate the uncertainty of the gradient and the *y*-intercept.

28 Identify a mathematical relationship between the velocity of the ball and time, including the uncertainty of the gradient and *y*-intercept.

Interpret

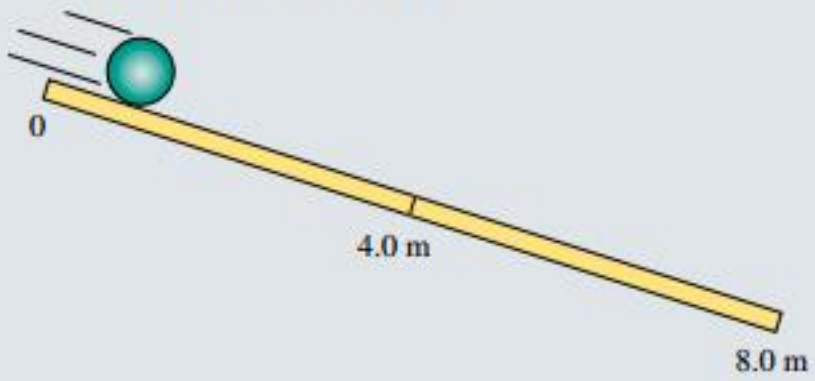
29 Two physics students conduct the following experiment from a very high bridge. Theo drops a 1.5 kg shot-put from a vertical height of 60.0 m. At the same time Benjamin throws a 100 g mass with an initial downwards velocity of $10.0\,m\,s^{-1}$ from a point 10.0 m above Theo.

- **a** Calculate how long it takes the shot-put to reach the ground.
- **b** Calculate how long it takes the 100 g mass to reach the ground.

30 At the start of an AFL football match, the umpire bounces the ball so that it travels vertically upwards and reaches a height of 15.0 m.

- **a** Calculate how long the ball takes to reach this maximum height.
- **b** One of the ruckmen can leap and reach to a height of 4.0 m with his hand. Calculate how long after the bounce the ruckman should try to contact the ball.

31 A billiard ball that is initially at rest rolls down a smooth ramp that is 8.0 m long. The acceleration of the ball is constant at $2.0\,m\,s^{-2}$.



- **a** Calculate the speed of the ball when it is halfway down the ramp.
- **b** Calculate the final speed of the ball.
- **c** Determine how long the ball takes to roll the first 4.0 m.
- **d** Determine how long the ball takes to travel the final 4.0 m.

Data analysis

DATA SET 1

The information below applies to Questions 1–4.

A student has conducted an experiment to answer the following research question.

What is the relationship between velocity and time for a falling basketball?

The experimental data was collected and processed and is presented in Figure 1.

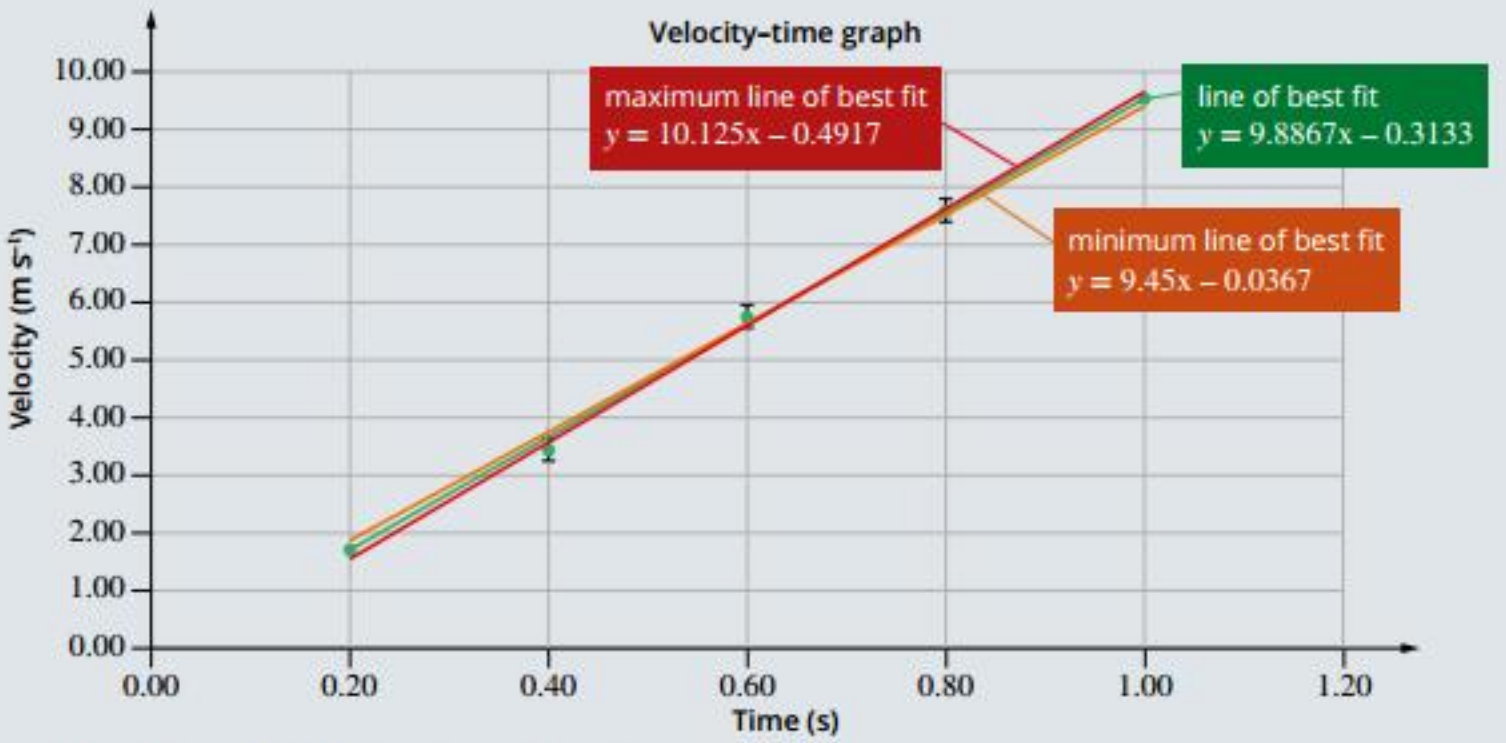


FIGURE 1 Graph of velocity against time for a falling basketball

Question 1 (1 mark)

Interpolate at what time the ball had an approximate velocity of 5.00 m s^{-1}.

Question 2 (2 marks)

Predict the launch velocity and acceleration of the ball using the equation for the line of best fit.

Question 3 (3 marks)

Use the lines of best fit to find a relationship between the velocity of the ball and time, including the uncertainty of the gradient and *y*-intercept.

Question 4 (2 marks)

Evaluate the accuracy of the experiment given acceleration due to gravity should be 9.8 m s^{-2}

CHAPTER

07 Classical mechanics

In the 17th century, Sir Isaac Newton published three laws that explain why objects in our universe move as they do. These laws became the foundation of a branch of physics called classical mechanics: the science of how and why objects move. The laws have become commonly known as the three laws of motion.

This chapter will use the three laws of motion of classical mechanics to describe the relationship between the forces acting on an object and its motion. It will also discuss the relationship between force, period of time and change in momentum (impulse).

Syllabus subject matter

CLASSICAL MECHANICS

- Describe the three laws of motion of classical mechanics and give examples of each. **7.2**
- Identify forces acting on an object. **7.1**
- Construct free-body diagrams representing forces such as the force due to gravity (weight), the normal force, tension, friction, drag and applied forces acting on an object. **7.1**
- Determine the resultant force acting on an object in one dimension. **7.1, 7.2**
- Solve problems using of the laws of classical mechanics and $a_{net} = \frac{F_{net}}{m}$. **7.2**
- Describe the concepts of momentum and impulse. **7.3, 7.4**
- Describe the principle of conservation of momentum. **7.5**
- Solve problems involving momentum, impulse, the conservation of momentum and collisions in one dimension using $p = mv$ and $\Sigma mv_{before} = \Sigma mv_{after}$. **7.3, 7.4, 7.5**
- Analyse the area under a force–time graph using geometric methods. **7.4**

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7.1 Forces

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- identify the forces acting on an object, including the force due to gravity (weight), the normal force, tension, friction, drag and applied forces
- draw free-body diagrams to show the forces acting on an object
- identify whether the forces acting on an object are balanced or unbalanced
- apply the vector model of forces, including vector addition, to find the net or resultant force acting on an object.

FORCES ACTING ON OBJECTS

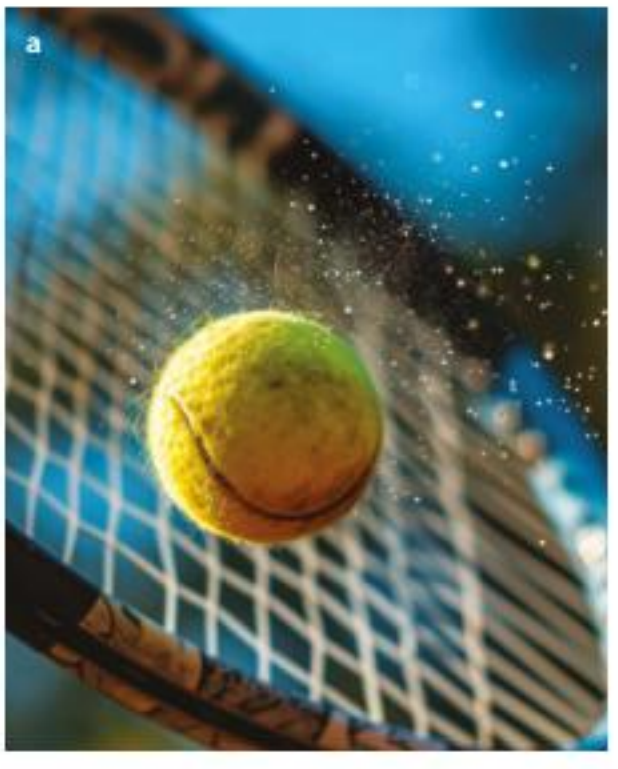
The previous chapter developed the concepts and ideas needed to describe the motion of a moving body. In this chapter, rather than simply describe the motion, you will investigate the forces that cause the motion to occur.

In simple terms, a **force** can be thought of as a push or a pull but forces exist in a wide variety of situations in everyday life and are fundamental to the nature of matter and the structure of the universe. Consider each of the photographs in Figure 7.1.1. For each situation, a force—a push or a pull—is acting.

In Figure 7.1.1, forces are acting in each of the situations. Some are applied directly to an object and some act on a body without touching it. Forces that act directly on a body are called **contact forces**, because the body will only experience the force while contact is maintained. Forces that act on a body at a distance are **non-contact forces**.

Contact forces are the easiest to understand and include the simple pushes and pulls that are experienced daily. Examples of contact forces include the forces between colliding billiard balls and the forces that act between you and your chair as you sit reading this book. Friction and drag forces are also contact forces.

A force is a measure of the push or pull on an object, and is measured in newtons (N). Force is a vector and so it requires a magnitude and a direction.



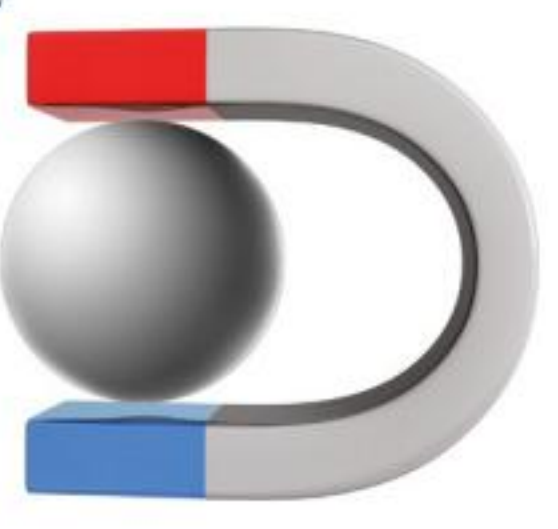


FIGURE 7.1.1 (a) At the moment of impact, both the tennis ball and the racquet strings will be distorted by the forces acting at that instant. (b) The rock climber is relying on the frictional force between his hands and feet and the rock face. (c) A continual force causes the clay to deform into the required shape. (d) The gravitational force between the Earth and the Moon is responsible for two high tides each day. (e) The ball is suspended in mid-air because of the magnetic forces of repulsion and attraction.

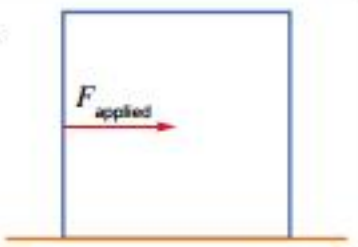
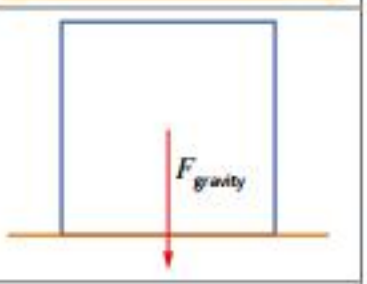
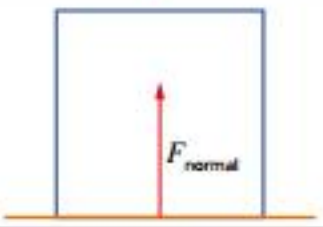
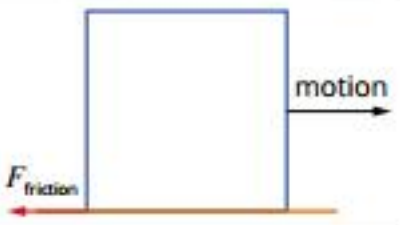
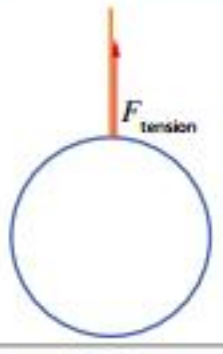
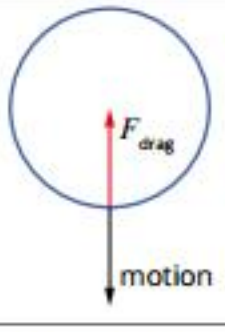
Non-contact forces occur when the object causing the push or pull is physically separated from the object that experiences the force. These forces are said to 'act at a distance'. Examples of non-contact forces include gravitation, magnetic and electric forces.

The amount of force acting on an object can be measured using the SI unit called the newton (N). The unit honours Sir Isaac Newton (1643–1727), who is still considered to be one of the most significant physicists to have lived. A force of one newton, 1 N, is approximately the force you have to exert when holding a 100 g mass against the downwards pull of gravity. In everyday life this is about the same as holding a small apple.

TYPES OF FORCES

Some forces, such as hitting a ball with a bat, or pushing a box, are easy to picture. Other forces are harder to describe, but it is useful to be able to identify them when solving problems. Some of the forces that you might encounter when solving simple force problems are described in Table 7.1.1.

TABLE 7.1.1 Some simple types of forces

Applied force	A force applied to an object by a person or another object. If you pull or push a cart, these are applied forces.	
Gravitational force	When you step on bathroom scales or measure flour, you are measuring mass (60kg or 100 g) which is different to weight. In physics, weight is the force due to gravity on an object's mass. On Earth, this gravitational force acts directly downwards.	
Normal reaction force	The normal reaction force opposes an applied force on a solid object. For example, a book on a table experiences an upward normal force opposing gravity. Similarly, when you push a wall, the normal force pushes back against your hands.	
Frictional force	The frictional force opposes motion. It arises when two surfaces are pressed together, and it depends on the types of surfaces. For example, if you push a book across a table, the frictional force opposes the book's motion.	
Tension	Tension is the force in a string or wire when pulled at both ends. For example, a pendulum bob experiences downward gravity and upward tension. Tension acts equally along the entire string or wire.	
Drag	Drag, caused by air resistance, slows motion. It can be useful, like slowing a parachutist as they fall, or unwanted, like on a truck. In Physics Units 1 and 2, you will often ignore air resistance for simplicity, but it is important to know its roll in resisting motion.	

RESULTANT FORCES AND EQUILIBRIUM

If more than one force acts on a body at the same time, the body behaves as if only one force is acting. This force is the vector sum of all the forces and is called the **resultant force** or **net force**, F_{net}.

When the net force is zero, the forces are said to be in **equilibrium**. The forces are balanced.

Free-body or force diagrams

A free-body diagram or force diagram is simply a picture that represents the forces acting upon an object. The forces are drawn to scale. Recall from Module 6.1 how to draw vectors in one dimension, and how to add and subtract them graphically and algebraically.

Consider an object with two forces acting on it: 20 N east and 40 N west. These forces can be illustrated in a simplified diagram, as shown in Figure 7.1.2.

FIGURE 7.1.2 A free-body or force diagram. As the force acting west is twice as large as the force acting east, its arrow is drawn twice as long. The arrowheads indicate that the vectors are in opposite directions.

On Earth, objects will also have the force due to gravity acting on them. Consider the bin sitting on a table shown in Figure 7.1.3. The forces acting are the weight of the object downwards and the normal reaction force from the table upwards. In the figure, these forces are drawn to be the same size but in opposite directions, as the object is at rest the forces must be in equilibrium so they must be equal and opposite. (Note that there is no need to draw a representative picture of the bin for a free-body diagram—a square or a circle will work just as well.)

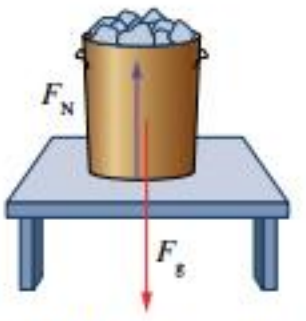


FIGURE 7.1.3 The forces acting on a bin sitting on a table. They are equal in magnitude but opposite in direction.

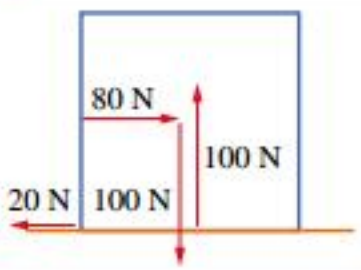
In Units 1 and 2 you will draw free-body diagrams showing forces acting in two dimensions, but will only solve problems mathematically with forces acting in one dimension (as illustrated in the above examples). In Units 3 and 4 you will also consider situations in which forces act in two or three dimensions.

The net force acting on an object can be found using the vector addition and subtraction techniques covered in Module 6.1. This is shown in the following worked example.

Worked example 7.1.1

FREE-BODY DIAGRAMS AND NET FORCE

A box has four forces acting on it: an applied force of 80 N right, a frictional force of 20 N left, a gravitational force of 100 N down and a normal reaction force of 100 N up. Construct a free-body diagram, and determine the resultant force acting on the box.

Thinking	Working
Construct a free-body diagram showing all the given forces.	
Apply a sign convention so that right and up are positive and left and down are negative.	Vertical forces (take right as positive): +80 N −20 N Horizontal forces (take up as positive): +100 N −100 N
Add the horizontal and vertical forces together.	$F_{horizontal} = 80 + (-20) = +60\,N$ $F_{vertital} = 100 + (-100) = 0\,N$
Use the sign convention to describe the resultant force.	$F_{net} = 60\,N$ right

➤ Try yourself 7.1.1

FREE-BODY DIAGRAMS AND NET FORCE

A box is dragged across the floor with a force of 25 N. A frictional force of 10 N opposes the motion. Construct a free-body diagram of the box and determine the net force acting on the box.

7.1 Review

SUMMARY

- A force is a push or a pull.
- A force is a vector quantity and therefore requires a magnitude and a direction.
- Forces that act directly on a body are called contact forces. Forces that act on a body at a distance are non-contact forces.
- The forces that act on an object include applied forces (a simple push or pull), as well as gravitational and frictional forces, the normal reaction force, tension and drag.
- The forces acting on an object can be represented by free-body or force diagrams.
- If forces acting on an object are balanced, they are said to be in equilibrium. If forces are not balanced, a net or resultant force will act on the object.
- Forces can be added using vector addition to find the resultant force, F_{net}, acting on an object.

KEY QUESTIONS

Describe

1 Recall the SI unit used to measure force.

2 List the features that are needed to fully describe a force.

3 Describe the difference between mass and weight.

Apply

4 A girl is standing still in the queue at the airport, holding a suitcase.

a Describe the forces acting on the suitcase and determine if they balanced.

b The girl puts the suitcase on the floor. Describe the forces acting on the suitcase now.

5 An applied force acts on a ball, making it roll across the floor. The ball slowly comes to a stop. Identify the unbalanced force that caused the ball to stop rolling.

Analyse

6 Draw free-body diagrams for:

a an apple sitting at rest on a table

b a cat pushing an apple to the right across a table so that the apple accelerates

c an apple falling towards the ground at constant velocity.

7 A textbook with a gravitational force of 15N sits at rest on top of a table. Calculate the normal force acting on the textbook.

8 A tennis ball at rest with a gravitational force of 0.6N is suspended from a string. Calculate the tension in the string.

9 A chair is pushed to the right with an applied force of 100N and experiences a frictional force of 20N to the left. Determine the resultant force acting on the chair.

7.2 Laws of motion

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the three laws of motion of classical mechanics
- use the second law of motion to calculate the force acting on an object for a given acceleration and mass
- identify an action–reaction pair.

The three laws of motion of classical mechanics describe how forces can be used to explain the motion of bodies. The first law describes what happens to a body when there is no net force on it. The second law explains acceleration when there is an unbalanced force acting. The third law states that all forces act in action–reaction pairs.

FIRST LAW OF MOTION

The first law of motion states that every object continues to be at rest, or continues with constant velocity, unless it experiences an unbalanced force. This is also called the law of inertia. Inertia is the tendency of an object to maintain its velocity. An object that is moving at constant velocity will keep moving unless an unbalanced force acts on it.

This is seldom observed in everyday life, due to the presence of forces such as friction and air resistance, which will eventually slow the motion of the object. To maintain constant motion, frictional forces must be balanced with some other force. For example, an object can keep moving at a constant velocity if it is driven by a motor.

The first law is often misunderstood due to a common misconception. People mistakenly think that an object that is moving at constant velocity must have a force causing it to move.

The first law of motion can be stated as:

An object will maintain a constant velocity unless an unbalanced, external force acts on it.

> **The first law of motion:**
> An object will maintain a constant velocity unless an unbalanced, external force acts on it.

This statement needs to be analysed in more detail by first examining some of the key terms used. The term 'maintain a constant velocity' implies that, if the object is moving, then it will continue to move with a velocity that has the same magnitude and direction. For example, if a car is moving at $12.0\,m\,s^{-1}$ south, then some time later it will still be moving at $12.0\,m\,s^{-1}$ south (Figure 7.2.1). It should also be noted that zero velocity is constant, so if the car is at rest at $0\,m\,s^{-1}$, then some time later it will still be at rest at $0\,m\,s^{-1}$. An object that is stationary will remain stationary, as long as the forces acting on it are balanced. For example, an object will fall due to the force of gravity, but will remain at rest when this force is balanced by the normal reaction force applied by a table.

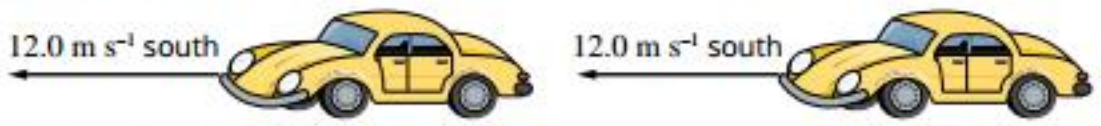


FIGURE 7.2.1 The car maintains a constant velocity

The use of the term 'unbalanced' in relation to the acting force implies that there must be a non-zero net force acting on the object. If the forces are balanced and the net force is equal to zero, then the object's velocity will remain constant. If the forces are unbalanced, then the velocity will change, or will not remain constant. This is illustrated in Figure 7.2.2 on page 254.

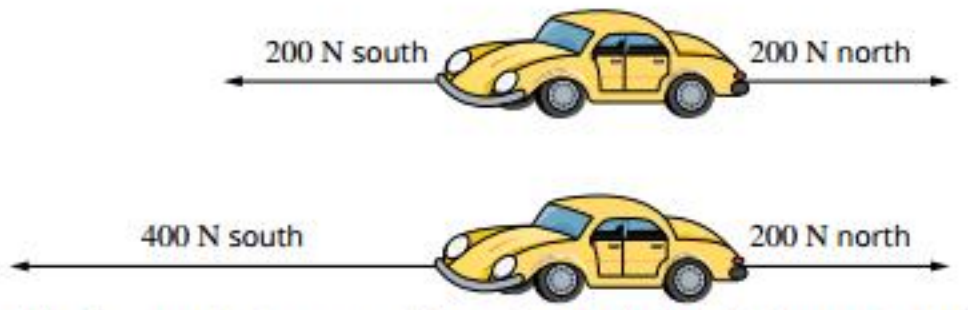


FIGURE 7.2.2 The forces on the top car are balanced, and so it will maintain a constant velocity. The forces on the bottom car are unbalanced: it has a net force in the forwards direction, so its velocity will change.

The term 'external', in relation to forces, implies that the forces are not internal. When forces are internal, they will have no effect on the motion of the object. For example, if you are sitting in a car and push forwards on the steering wheel then the car will not move forwards due to this force. In order for you to push forwards on the steering wheel, you must push backwards on the seat. Both the steering wheel and the seat are attached to the car; therefore, there are two forces acting on the car that are equal and in the opposite direction to each other, as shown in Figure 7.2.3. All internal forces must result in balanced forces on the object and therefore they will not change the velocity of the object.

FIGURE 7.2.3 This driver is applying internal forces on a car. These internal forces will balance and cancel each other.

The effects of forces

In Module 7.1, you found the resultant or net force acting on an object. Applying a net force can cause an object to speed up, to slow down, to start moving, to stop moving or to change its direction. The effect depends on the direction of the force in relation to the direction of the velocity vector of the object experiencing the force (Figure 7.2.4). The effect of external forces is summarised in Table 7.2.1.

TABLE 7.2.1 The effect of the application of a force and the relationship between the direction of the force and the velocity

Relationship between velocity and force	Effect of force
force applied to object at rest	object starts moving
force in same direction as velocity	magnitude of velocity increases (object speeds up)
force in opposite direction to velocity	magnitude of velocity decreases (object slows down)
force perpendicular to velocity	direction of velocity changes (object turns); more on this in units 3 and 4

In all cases, the effect of a force is to change the velocity of an object. A force can change the magnitude of the velocity, the direction of the velocity, or both the magnitude and the direction of the velocity.

FIGURE 7.2.4 The upwards thrust force on a rocket has the effect of speeding it up, whereas the upwards drag force on a parachute has the effect of slowing the descent of a parachutist.

Stating the first law of motion in different ways

Ludwig Wittgenstein, an Austrian–British philosopher, stated that 'understanding means seeing that the same thing said different ways is the same thing'. To truly understand the first law, you should be able to state it in different ways yet still recognise it as being consistent with the first law.

All of these statements are consistent with the first law of motion:

- An object will maintain a constant velocity unless an unbalanced, external force acts on it.
- An object will continue with its motion unless an unbalanced, external force is applied.
- An object will not continue with a constant velocity if an unbalanced, external force is applied.
- A body will either remain at rest or continue with constant speed in a straight line (constant velocity) unless it is acted on by a net force.
- If an unbalanced, external force is applied, then an object's velocity will change.
- If a net force is applied, then an object's velocity will change.
- If no net force is applied, an object will not accelerate.
- If a net force is applied, an acceleration will result.
- Net forces cause acceleration.
- No force, no acceleration.
- Constant velocity means no net force is applied.

Inertia

Inertia is resistance to a change in motion of an object. It is related to the mass of the object. As the mass of the object increases, the inertia increases and therefore it becomes more difficult:

- to start it moving if it is stationary
- to stop it moving
- to change its direction of motion.

You can experience the effect of inertia when you push a trolley in a supermarket. If the trolley is empty, it is relatively easy to start pushing it, or to pull it to a stop when it is already moving. It is also easy to turn a corner. If you fill the trolley with heavy groceries, you notice that it becomes more difficult to move. It requires more force to make the trolley start moving when it is at rest, and it becomes more difficult to pull it to a stop if it is already moving. It also requires more force to change the trolley's direction.

It is important to note that the effect of inertia is independent of gravity. Inertia depends on mass, and weight force due to gravity also depends on mass, so it is a common misunderstanding to think that the effects of inertia only apply in the presence of gravity. However, it would be just as difficult to change the state of motion of the trolley in space as it is in the supermarket aisle.

The first law of motion and inertia are related. Due to inertia, an object will continue with its motion unless a net force acts on it. You could experience the connection between the first law of motion and inertia when standing up on public transport. Imagine standing up in a bus that is initially at rest and then starts moving forwards. If you are not holding on to anything, you might stumble backwards as though you have been pushed backwards. However, you have not been pushed backwards; the bus has started moving forwards and, because you have inertia, your mass resists the change in motion. According to the first law of motion, your body is simply maintaining its original state of being motionless until an unbalanced force acts to accelerate it. When the bus comes to a sudden stop, your body again resists the change by continuing to move forwards until an unbalanced force acts to bring it to a stop.

Frictional forces

A mathematical analysis of frictional forces is beyond the scope of this course. However, an understanding of how friction acts is useful when analysing the forces acting on an object. Friction is a force that opposes movement. Suppose you want to push your textbook along the table. As you start to push the book, you find that the book does not move at first. You then increase the force that you apply. At a certain critical value, the book starts to move.

There is a maximum frictional force that resists the start of the slide. This force is called the static friction force, F_s. Once the book begins to slide, a much lower force than F_s is needed to keep the book moving. This force is called the kinetic friction force and is represented by F_k. The graph in Figure 7.2.5 shows how the force required to move an object changes as static friction is overcome.

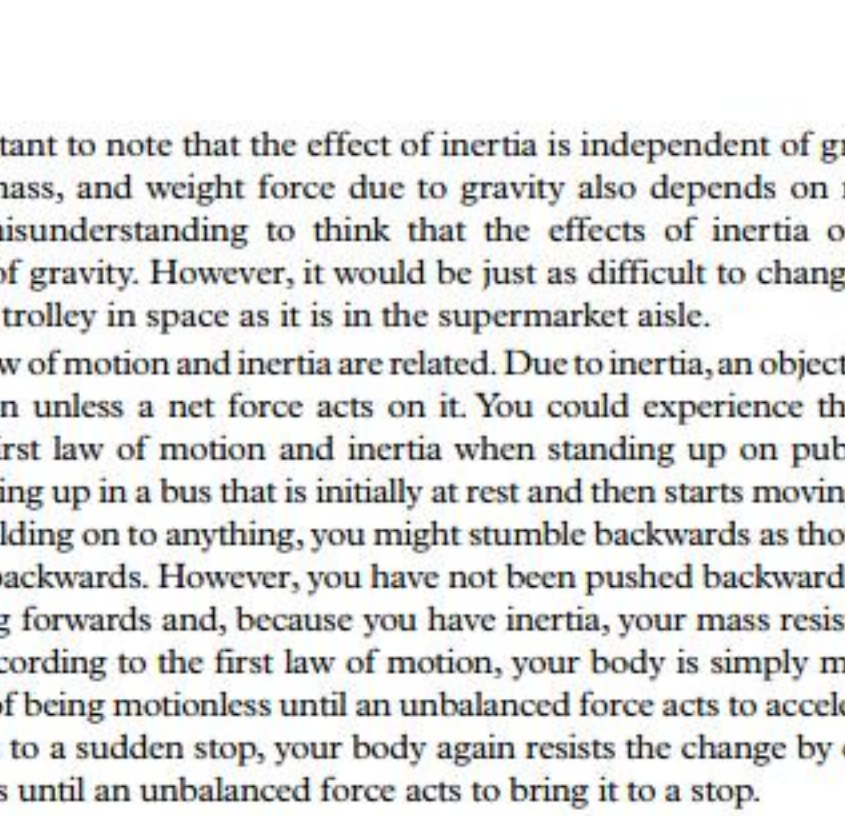


FIGURE 7.2.5 To get things moving, the static friction between an object and the surface must be overcome. This requires a larger force than is needed to maintain constant velocity.

Even the smoothest surfaces are quite jagged at the microscopic level. So, when the book is resting on the table, the jagged points of its bottom surface are settled into the valleys of the surface of the table and this helps to resist attempts to slide the book. Once the book is moving, the surfaces do not have any time to settle into each other, so less force is required to keep the book moving.

Another fact that helps to explain friction arises from the forces of attraction between the atoms and molecules of the two different surfaces that are in contact. These surfaces produce weak bonding between their respective particles, so before one surface can move across the other, these bonds must be broken. This extra effort adds to the static friction force. Once there is relative motion between the surfaces, the bonds cannot re-form.

In everyday life, there are situations in which friction is desirable (such as walking) and others in which it is a problem. Consider the moving parts within the engine of a car. Friction can rob an engine of its fuel economy and cause it to wear out. Oils and lubricants are used to prevent moving metal surfaces from touching. If the moving surfaces actually moved over each other, they would quickly wear, producing metal filings that could damage the engine. Instead, a thin layer of oil separates metal surfaces. The oils are chosen on the basis of their viscosity (thickness). For example, low viscosity oils can be used in the engine, but heavier oils are needed in the gearbox and differential of the car, where greater forces are applied to the moving parts. Maglev trains (Figure 7.2.6) also require the reduction of friction. These trains use electromagnets to levitate off the tracks so that they can reach very high speeds.

FIGURE 7.2.6 This magnetic levitation train in China rides 1 cm above the track, so the frictional forces are negligible. The train is propelled by a magnetic force to a cruising speed of about 430 km h^{-1}.

At other times, friction is essential. For example, if there is ice on the road when driving to the snowfields, drivers are required to fit chains to their cars. When driving over a patch of ice, the chains break through the ice and the car is able to grip the road. Similarly, friction is required within the car's brakes when the driver wants to slow down. In fact, modern brake pads are specially designed to maximise the friction between them and the brake drum or disk.

Observing the first law of motion

An object in motion will eventually stop. For example, a pen sliding across a table is a good example of the first law of motion. The motion does not continue, so a net force must be acting. In this case, the force is not obvious. Confusion sometimes arises if the force due to friction is overlooked. Friction is a force that always acts in the opposite direction to the motion of objects. Air resistance is also a force that is often overlooked, as is the force due to gravity. By ignoring the effects of these important forces, it can be easy to come to the incorrect conclusion that the natural state of any object is to be at rest. By considering all the external forces acting on an object, it becomes clear that the natural state of any object is to maintain the velocity it currently has.

You can observe the first law of motion in the classroom by trying the following activities.

- Place some objects such as an eraser, a highlighter or a bottle of liquid paper on a piece of paper. Pull the paper slowly and observe what happens. Then pull the paper very quickly and observe what happens. A quick pull demonstrates the principle of inertia and the first law of motion.
- Make a pile of 20c coins on a smooth surface. Place them all tails-up except for the bottom coin. See if you can knock out the bottom coin by flicking it with another tails-up 20c coin.
- Put your right hand on your right shoulder, palm up, and place a coin on your elbow. Fling your arm down and see if you can catch the coin. The coin should remain motionless long enough for you to catch it.

SECOND LAW OF MOTION

In Module 7.1, you learnt that unbalanced forces acting on an object mean that a net or resultant force is acting on it. The net force can be found using vector addition. The section on the first law of motion states that a net force will produce an acceleration. **The second law of motion** makes the quantitative connection between force, mass and acceleration. It states that the net acceleration, a_{net}, of a body experiencing an unbalanced or net force, F_{net}, is directly proportional to the net force acting on it and inversely proportional to the mass, m, of the body. This equation is also commonly written as:

$$a_{net} = \frac{F_{net}}{m} \text{ or } F_{net} = ma_{net}$$

The second law of motion:

$a_{net} = \frac{F_{net}}{m}$ or $F_{net} = ma_{net}$

where

a_{net} is the net acceleration of an object ($m\,s^{-2}$)

F_{net} is the net force applied to the object (N)

m is the mass of the object (kg)

One newton is the force needed to accelerate a mass of 1 kg at $1\,m\,s^{-2}$. The unit of force is the units of mass and acceleration combined, or $kg\,m\,s^{-2}$. This unit was renamed the newton (N) in honour of Sir Isaac Newton.

One of the implications of the second law is that, for a given mass, a greater acceleration is achieved by applying a greater force. This is shown in Figure 7.2.7. Doubling the applied force will double the acceleration of the object. In other words, acceleration is proportional to the net force applied. Notice also in Figure 7.2.7 that the acceleration of the object is in the same direction as the net force applied to it.

The second law of motion also explains how acceleration is affected by the mass of an object. For a given force, the acceleration of an object will decrease with increased mass. In other words, acceleration is inversely proportional to the mass of an object. This is shown in Figure 7.2.8.

The second law helps you to understand why a motorcycle can accelerate from traffic lights at a greater rate than a car or a truck. Although the engine of a car or truck often has more power than that of a motorcycle, the motorcycle has far less mass. This allows the motorcycle to accelerate more quickly than a car or truck (Figure 7.2.9).

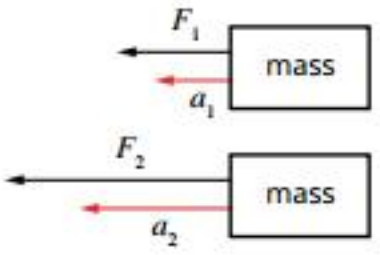


FIGURE 7.2.7 Given the same mass, a larger force will result in a larger acceleration. If the force is doubled, then the acceleration is also doubled.

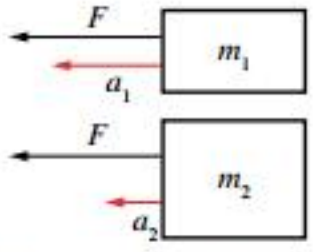


FIGURE 7.2.8 Given the same force, a larger mass will result in a lower acceleration. If the mass is doubled, then the acceleration is halved.

FIGURE 7.2.9 The lower mass of motorcycles enables them to accelerate faster than cars and trucks.

Observing the second law of motion

The equation $F_{net} = ma_{net}$ is used to calculate the force that causes a mass to accelerate. Mass is something that is easily observed. You can measure the mass of an object on a balance. You can hold two masses in your hands and feel their effect. Similarly, you can observe acceleration, such as when a car accelerates away from the traffic lights. Force, on the other hand, is not something you can see. However, you can observe the effect of a force.

Worked example 7.2.1

CALCULATING THE FORCE THAT CAUSES AN ACCELERATION

Calculate the net force causing a 5.50 kg mass to accelerate at 3.75 m s^{-2} west.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$m = 5.50\,\text{kg}$ $a_{net} = 3.75\,\text{m s}^{-2}$ west
Apply the equation for force from the second law of motion.	$F_{net} = ma_{net}$ $= 5.50 \times 3.75$ $= 20.6\,\text{N}$
Give the direction of the net force, which is always the same as the direction of the acceleration.	$F_{net} = 20.6\,\text{N}$ west

➤ Try yourself 7.2.1

CALCULATING THE FORCE THAT CAUSES AN ACCELERATION

Calculate the net force causing a 75.8 kg runner to accelerate at 4.05 m s^{-2} south.

The first equation for uniform acceleration, which is discussed in Module 6.4 on page 220, can be combined with the second law of motion to calculate changes in time or velocity.

The first equation for uniform acceleration is:

$$v = u + at$$

This can be rearranged to give:

$$a = \frac{v - u}{t}$$

Combining this with $F_{net} = ma_{net}$ gives:

$$F_{net} = m\left(\frac{v - u}{t}\right)$$

The relationship between net force, mass and the velocity of an object is given by this equation:

$$F_{net} = m\left(\frac{v - u}{t}\right)$$

where

F_{net} **is the force applied to the object (N)**
m **is the mass of the object (kg)**
u **is the initial velocity (m s^{-1})**
v **is the final velocity (m s^{-1})**
t **is the time (s)**

Worked example 7.2.2

CALCULATING THE FINAL VELOCITY OF AN ACCELERATING MASS

Calculate the final velocity of a 225 kg scooter that accelerates for 2.00 s from rest due to a force of 2430 N north.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$m = 225\,\text{kg}$ $t = 2.00\,\text{s}$ $u = 0\,\text{m s}^{-1}$ $F_{net} = 2430\,\text{N north}$
Apply a variation of the equation for force from the second law of motion.	$F_{net} = m\left(\frac{v-u}{t}\right)$ $(v-u) = \frac{F_{net}t}{m}$ $v = \frac{F_{net}t}{m} + u$ $= \frac{2430 \times 2.00}{225} + 0$ $= 21.6\,\text{m s}^{-1}$
Give the direction of the final velocity as being the same as the direction of the force.	$v = 21.6\,\text{m s}^{-1}$ north

➤ Try yourself 7.2.2

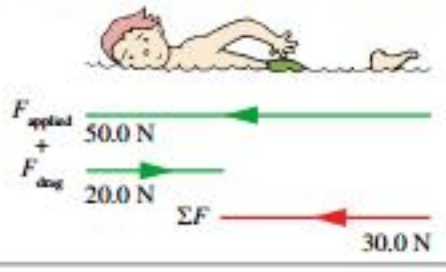
CALCULATING THE FINAL VELOCITY OF AN ACCELERATING MASS

Calculate the final velocity of a 307 g fish that accelerates for 5.20 seconds from rest due to a force of 0.250 N left.

Forces do not always act alone. Mostly, more than one force will act on an object at any time. The overall effect of the forces depends on the direction of each of the forces. For example, some forces act together and some may oppose each other. When using the second law of motion, it is important to use the net, or resultant, force in the calculation. As forces are vectors, they can be added or combined using the techniques discussed in Module 6.1. Consider the following worked examples.

Worked example 7.2.3

ACCELERATION OF AN OBJECT WITH MORE THAN ONE FORCE ACTING ON IT

A swimmer whose mass is 75 kg applies a force of 50.0 N as he starts a lap. The water opposes his efforts to accelerate with a drag force of 20.0 N. Calculate his initial acceleration.	
Thinking	**Working**
Determine the individual forces acting on the swimmer, and apply the vector sign convention.	$F_1 = 50.0\,\text{N forwards} = 50.0\,\text{N}$ $F_2 = 20.0\,\text{N backwards} = -20.0\,\text{N}$
Determine the net force acting on the swimmer.  	$F_{net} = F_1 + F_2$ $= 50.0 + (-200)$ $= +30.0\,\text{N or } 30.0\,\text{N forwards}$
Use the second law of motion to determine acceleration.	$a_{net} = \frac{F_{net}}{m}$ $= \frac{30.0}{75}$ $= 0.40\,\text{m s}^{-2}\text{ forwards}$

➤ Try yourself 7.2.3

ACCELERATION OF AN OBJECT WITH MORE THAN ONE FORCE ACTING ON IT

A car with a mass of 900.0 kg applies a driving force of 3000.0 N as it starts moving. Friction and air resistance oppose the motion of the car with a force of 750.0 N. Calculate the initial acceleration of the car.

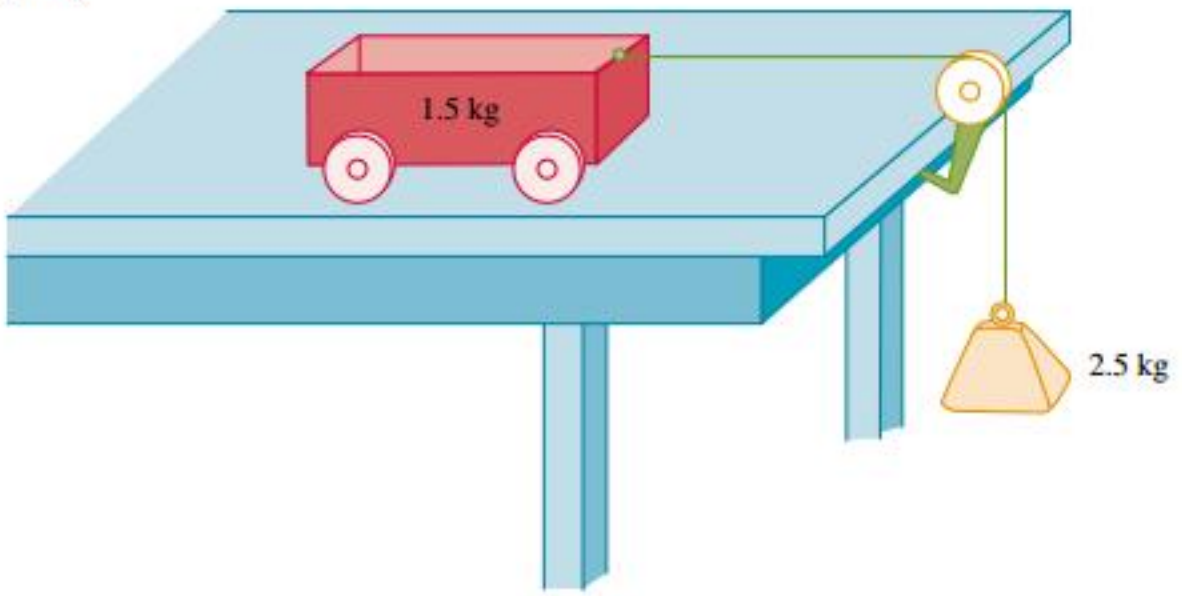
If an object is allowed to fall under the influence of gravity, and air resistance and frictional forces are ignored, then $F_{net} = F_g = mg$.

Remember that acceleration due to gravity is $g = 9.8\,m\,s^{-2}$ downwards.

Worked example 7.2.4

CALCULATING THE ACCELERATION OF A CONNECTED BODY

A 1.5 kg dynamics cart is connected by a cord to a 2.5 kg mass as shown. The cord is placed over a pulley and the mass is allowed to fall under the influence of gravity.



a Calculate the acceleration of the cart, assuming that the cart is unhindered by friction.

Thinking	Working
As the mass falls, the cart will move to the right. Therefore, both the downwards movement of the mass and the rightwards movement of the cart will be considered positive motion. Remember: $g = 9.8\,m\,s^{-2}$ down	$m_1 = 2.5\,kg$ $m_2 = 1.5\,kg$ $g = +9.8\,m\,s^{-2}$
Determine the forces acting on the system. The only force acting on the combined system of the cart and mass is the weight of the falling mass.	$F_{net} = F_g$ $= m_1 g$ $= 2.5 \times 9.8$ $= 24.5$ $= 25\,N$ in the positive direction
Calculate the mass being accelerated. This net force has to accelerate not only the cart but also the falling mass.	$m_1 + m_2$ $= 2.5 + 1.5$ $= 4.0\,kg$
Use the second law of motion to determine acceleration.	$a = \frac{F_{net}}{m}$ $= \frac{24.5}{4.0}$ $= 6.1\,m\,s^{-2}$ to the right

b Calculate the acceleration if a frictional force of 8.5 N acts against the cart.	
Thinking	**Working**
Write down the data that is given. Apply the sign convention to vectors.	$m_1 = 2.5\,\text{kg}$ $m_2 = 1.5\,\text{kg}$ $g = +9.8\,\text{m s}^{-2}$ $F_f = 8.5\,\text{N left} = -8.5\,\text{N}$
Determine the forces acting on the system. There are now two forces acting on the combined system of the cart and mass: the weight of the falling mass and friction.	$F_{net} = F_g + F_f$ $= 24.5 + (-8.5)$ $= 16.0\,\text{N}$
Use the second law of motion to determine acceleration.	$a_{net} = \frac{F_{net}}{m}$ $= \frac{16.0}{4.0}$ $= 4.0\,\text{m s}^{-2}$

➤ Try yourself 7.2.4

CALCULATING THE ACCELERATION OF A CONNECTED BODY

A 0.60 kg dynamics cart is connected by a cord to a 1.5 kg mass. The cord is placed over a pulley and the mass is allowed to fall under the influence of gravity.

a Determine the acceleration of the cart, assuming that the cart is unhindered by friction.

b Calculate the acceleration if a frictional force of 4.2 N acts against the cart.

Air resistance and the feather and hammer experiment

When two objects with different masses fall under the influence of the force due to gravity in the absence of air resistance, they will both fall at the same rate. That is, their accelerations will be the same. They will have the same displacement over the same time and will hit the ground at the same time if dropped from the same height. This seems counterintuitive, because you usually see the effects of air resistance (drag). If you dropped a feather and a hammer on the Moon, you would find that they fall at the same velocity because there is no atmosphere and, therefore, no air resistance. If you search online, you can find footage of an experiment performed by popular physicist Brian Cox, who uses a bowling ball and a feather in a NASA vacuum chamber to demonstrate this phenomenon.

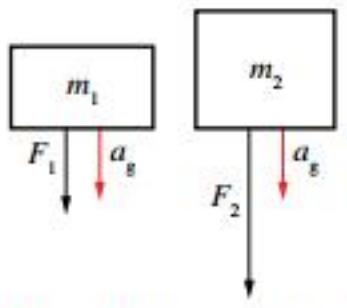


FIGURE 7.2.10 Given the same acceleration, a larger mass must have a larger force acting on it. If the mass is doubled, then the force is doubled.

If you understand that all objects accelerate due to gravity at the same rate in a vacuum, the common misconception is that the force due to gravity is the same on all objects. This is not true. In fact, the force due to gravity is larger on larger objects and smaller on smaller objects. You must not forget that the objects have different masses. A larger mass experiences a greater force due to gravity (weight) than a smaller mass, but it also has more inertia so it requires that greater force to achieve the same acceleration. Refer to Figure 7.2.10 to see how this works.

If you consider the relationship between acceleration and mass, and the relationship between acceleration and force, then:

$$a = \frac{F}{m}$$

If m_2 is ten times the mass of m_1, then the force due to gravity on m_2 is ten times the force due to gravity on m_1. Consider the acceleration of both masses:

$$a_1 = \frac{F_1}{m_1}$$

If $F_2 = 10F_1$ and $m_2 = 10m_1$, then:

$$\begin{aligned} a_2 &= \frac{F_2}{m_2} \\ &= \frac{10F_1}{10m_1} \\ &= \frac{F_1}{m_1} \\ &= a_1 \end{aligned}$$

This proof shows that the ratio of force to mass is equal for all combinations of force and mass under the same effects due to gravity. This proves that all masses will experience the same acceleration if air resistance is removed.

Why does this experiment not work on Earth?

When you see a feather floating down through the air, you know that it is accelerating at a rate far less than a hammer falling from the same height. From the previous section, you will know that the hammer and the feather have forces due to gravity acting on them that are proportional to their mass. They do not fall at the same rate because of the force of air resistance. Remember, the second law of motion says the acceleration is proportional to the net force acting on an object, which means you must consider all the forces acting on an object to determine the acceleration.

Air resistance is a force that results from air molecules colliding with the object. The faster the object moves, the greater the air resistance. In addition, the greater the surface area perpendicular to the direction of motion, the greater the air resistance. This force, which acts in the opposite direction to the motion of an object, is significant when compared with the weight of the feather, but insignificant when compared with the weight of the hammer. As a result, this force has a noticeable effect on the feather's acceleration but makes no noticeable difference to the hammer's acceleration.

In Figure 7.2.11, the force of air resistance is denoted as F_{AR} and is the same size on both objects. The difference between the two objects is the downwards weight force (due to gravity). Figure 7.2.11 also shows that the acceleration of the thinner object is much less than the acceleration of the thicker object. This is the observation that often causes misconceptions.

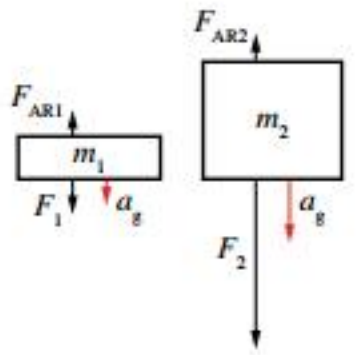


FIGURE 7.2.11 The effect of air resistance on an object depends on the surface area perpendicular to the motion and the speed of the object.

THIRD LAW OF MOTION

Newton realised that when a body exerts a force on another body, then the forces exist in pairs and that each force in the pair acts on a different object. Figure 7.2.12 shows a hammer hitting a nail on the head. Both the hammer and the nail experience forces during this interaction. The nail experiences a downwards force as the hammer hits it. When the nail is hit, it moves a distance into the wood. As it hits the nail, the hammer experiences an upwards force that causes the hammer to stop. These forces are known as an action–reaction pair and are shown in Figure 7.2.13.

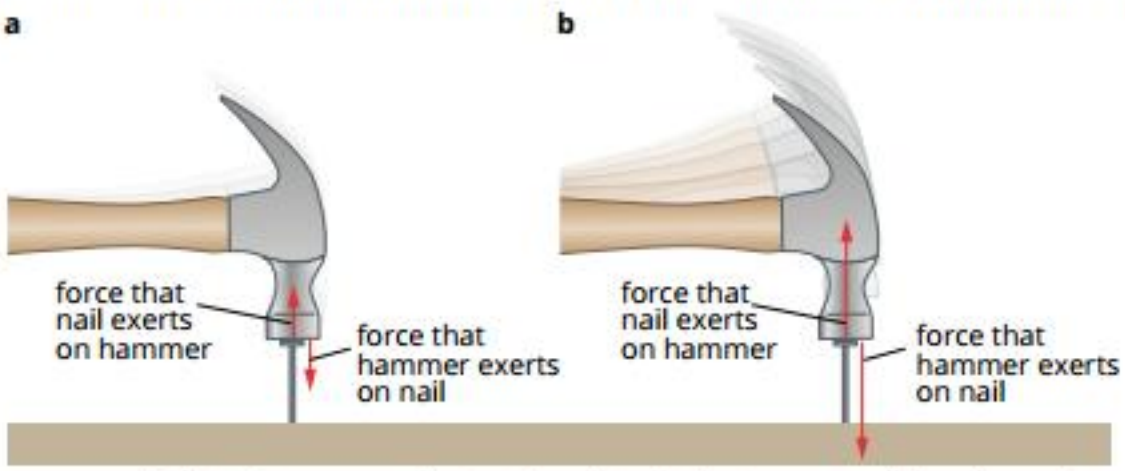

a
b
force that nail exerts on hammer
force that hammer exerts on nail
force that nail exerts on hammer
force that hammer exerts on nail

FIGURE 7.2.13 (a) As the hammer gently taps the nail, both the hammer and the nail experience small forces. (b) When the hammer smashes into the nail, both the hammer and the nail experience large forces. In both cases, these forces are designated by $F_{\text{on nail by hammer}}$ and $F_{\text{on hammer by nail}}$.

FIGURE 7.2.12 A hammer hitting a nail is a good example of an action–reaction pair and the third law of motion.

It is important to note that, regardless of whether the hammer exerts a small or a large force on the nail, the nail will exert exactly the same-size force back on the hammer.

The third law of motion of classical mechanics states that when one body exerts a force on another body (an action force), the second body exerts an equal force in the opposite direction on the first (the reaction force):

$$F_{\text{on A by B}} = -F_{\text{on B by A}}$$

To simplify the notation, the following convention will be used, where the first subscript is the body experiencing the force.

$$F_{\text{AB}} = F_{\text{on A by B}}$$

It is important to recognise that the action force and the reaction force in the third law act on *different* objects and so should never be added together; their effect will only be on the object on which they act (Figure 7.2.14). The third law of motion applies not only to forces between objects that are in direct contact, but also to non-contact forces, such as the force due to gravity between objects.

If we take the force of gravity acting on you due to Earth's mass ($F_{\text{on you by Earth}}$) as an action force, the reaction force is the force of gravity acting on Earth due to your mass ($F_{\text{on Earth by you}}$). It is strange to think that your mass can create a gravitational force as strong as the mass of the Earth, but there is a lot more of the Earth to be attracted to your gravitational field. The only reason Earth does not shift every time you jump is explained by the second law of motion, as Earth's significant mass means it requires a much greater force to make it move.

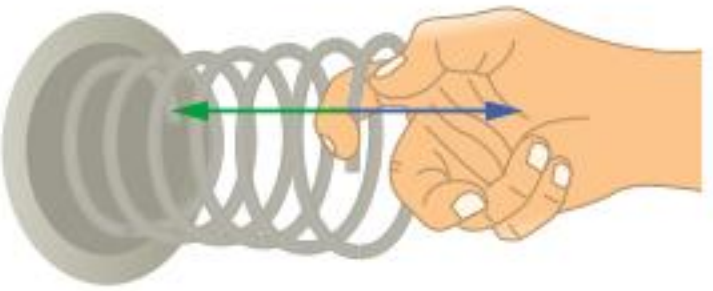


FIGURE 7.2.14 An action–reaction pair. The hand pulls on the spring and the spring pulls back on the hand with an equal and opposite force.

A common misconception that arises when considering the third law of motion is the belief that, if a large mass collides with a smaller mass, then the larger object exerts a larger force and the smaller object exerts a smaller force. This is not true. If you witnessed the collision between the car and the bus in Figure 7.2.15c, you would see the car undergoing a large deceleration, while the bus undergoes only a small acceleration.

Although the force on each object is the same size, the resulting acceleration may not be. This is because the rate of acceleration depends on the mass of the objects concerned (from the second law of motion). Sometimes, when the objects have very different masses, the effect of one force in the pair is much more noticeable. For example, if you stub your toe on a large, heavy rock, the force exerted on your toe by the rock causes your foot to decelerate significantly. The equal and opposite force exerted by your toe on the rock does not cause significant acceleration of the rock, because of its much greater mass.

From the second law of motion, you know that the same force acting on a larger mass will result in a smaller acceleration. This is the effect seen in the situation of the car colliding with the bus. Because of the car's small mass, the force acting on the car will cause the car to undergo a large deceleration. The occupants may be seriously injured as a result of this. The force acting on the bus is equal in size, but is acting on a much larger mass. As a result, the bus will have a relatively small acceleration and the occupants will not be as seriously affected.

The third law of motion:

For every action force, there is an equal and opposite reaction force.

The forces in an action–reaction pair:

- are the same magnitude (size)
- act in opposite directions
- are exerted on two different objects.

Identifying the action and reaction forces

When analysing a situation to determine the action and reaction forces according to the third law of motion, it is helpful to be able to label the force vectors systematically. A good strategy for labelling force vectors is to use the capital letter F to represent the force and then to include a subscript consisting of the word 'on' and the thing on which the force is acting, and then the word 'by' and the thing that is applying the force.

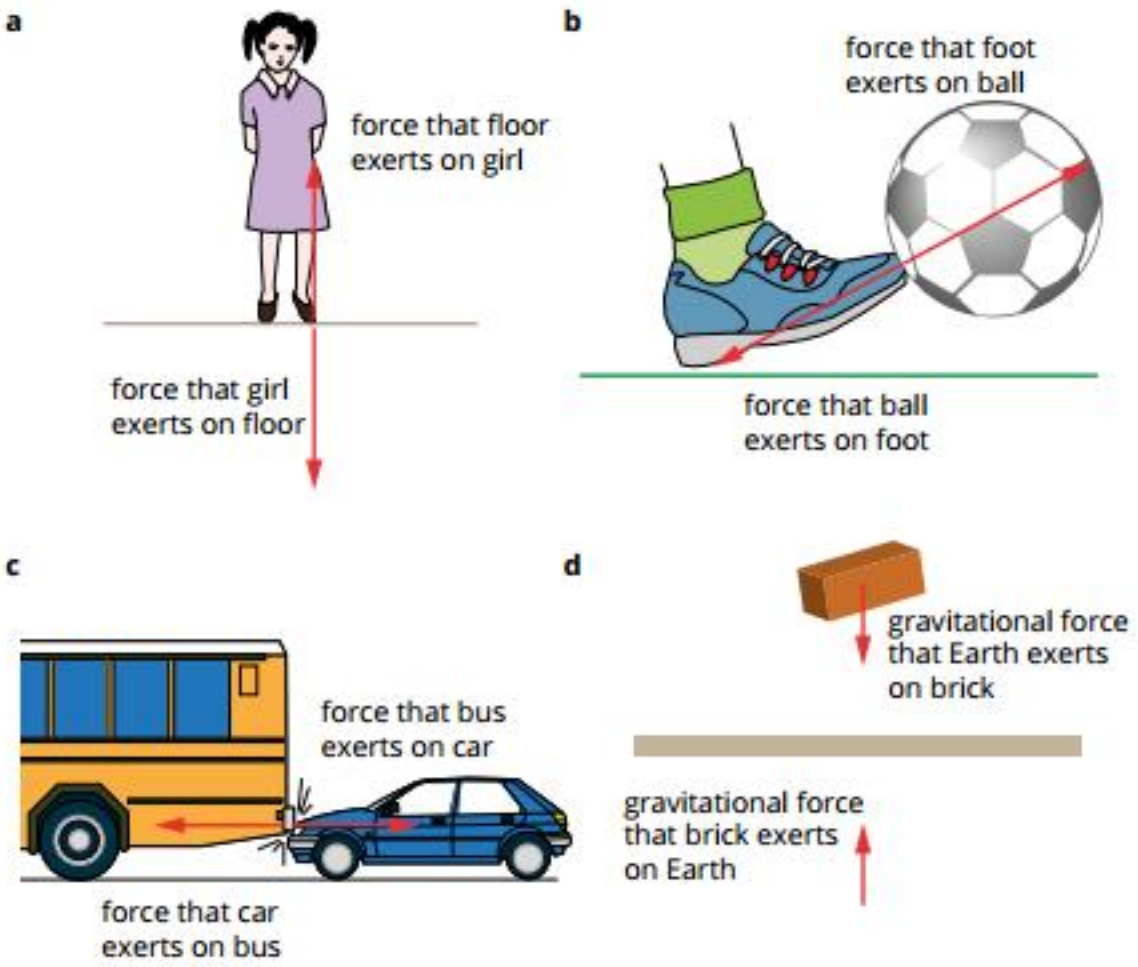

a
force that floor exerts on girl
force that girl exerts on floor
b
force that foot exerts on ball
force that ball exerts on foot
c
force that bus exerts on car
force that car exerts on bus
d
gravitational force that Earth exerts on brick
gravitational force that brick exerts on Earth

FIGURE 7.2.15 Some action–reaction pairs

The equal and opposite force is then labelled with a capital F and a subscript with the objects in reverse. For example, the action and reaction force vector arrows shown in Figure 7.2.15 can be labelled as shown in Table 7.2.2.

TABLE 7.2.2 Labels of action and reaction force vectors in Figure 7.2.15

	Action vector	Reaction vector
a	$F_{\text{on floor by girl}}$	$F_{\text{on girl by floor}}$
b	$F_{\text{on ball by foot}}$	$F_{\text{on foot by ball}}$
c	$F_{\text{on bus by car}}$	$F_{\text{on car by bus}}$
d	$F_{\text{on Earth by brick}}$	$F_{\text{on brick by Earth}}$

Note that it does not matter which force is considered the action force and which is considered the reaction force. You could consider the force on the girl by the floor to be the action force and the force on the floor by the girl to be the reaction force. It does not matter, as long as you label them clearly. They are always equal in magnitude and opposite in direction.

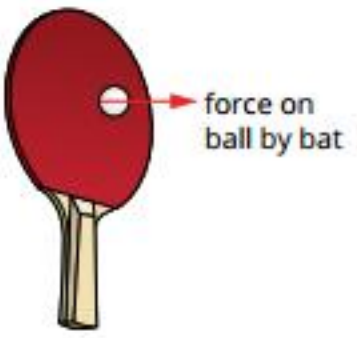
Observing the third law of motion

The second and third laws of motion can be observed in the classroom if you have two dynamics carts with wheels that are free to roll on a smooth surface such as a bench or desk. If the two carts are placed in contact with each other, and the plunger is activated on *one* of the carts, you will observe that both carts roll backwards. This is because of the action–reaction force pair described by the third law. If the two carts have similar masses, you will observe that they accelerate apart at a similar rate. If one cart is heavier than the other, you will observe that the lighter cart accelerates at a faster rate. This is because the forces acting on both carts are equal in magnitude and so, according to the second law of motion, the smaller mass will experience a greater acceleration.

Worked example 7.2.5

APPLYING THE THIRD LAW OF MOTION

In the diagram below, a table-tennis bat is in contact with a table-tennis ball and one of the forces is given.



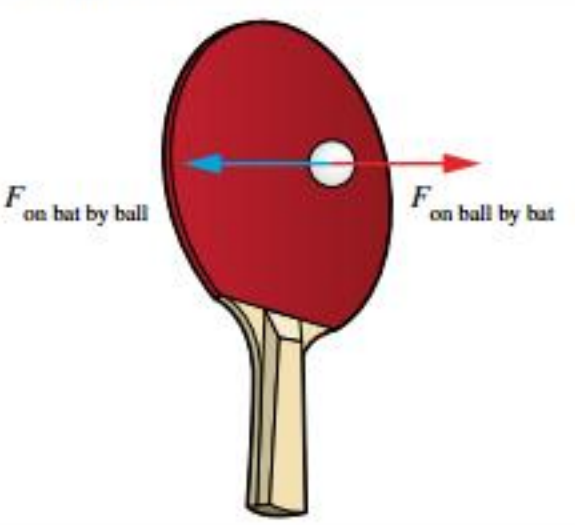
a Label the given force using the system '$F_{\text{on}\ \_\_\_\_\_\ \text{by}\ \_\_\_\_\_}$'.

Thinking	Working
Identify the two objects involved in the action–reaction pair.	The bat and the ball
Identify which object is applying the force and which object is experiencing the force, for the force vector shown.	The force vector shown is a force from the bat on the ball.
Use the system of labelling action and reaction forces '$F_{\text{on}\ \_\_\_\_\_\ \text{by}\ \_\_\_\_\_}$' to label the action force.	$F_{\text{on ball by bat}}$

b Label the reaction force to the given force using the system '$F_{\text{on}\ \_\_\_\_\_\ \text{by}\ \_\_\_\_\_}$'.

Use the system of labelling action and reaction forces '$F_{\text{on}\ \_\_\_\_\_\ \text{by}\ \_\_\_\_\_}$' to label the reaction force.	$F_{\text{on bat by ball}}$

c Draw the reaction force on the diagram, showing its size and location.

Use a ruler to measure the length of the action force and construct a vector arrow in the opposite direction with its tail on the point of application of the reaction force.	

➤ Try yourself 7.2.5

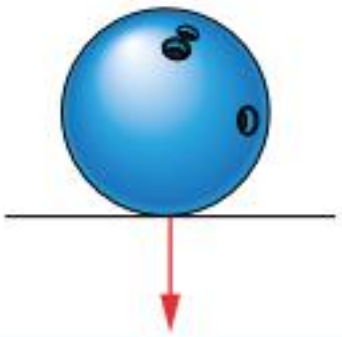
APPLYING THE THIRD LAW OF MOTION

In the diagram below, a bowling ball is resting on the floor, and one of the forces is given. Copy the diagram into your book and complete the following.

a Label the given force using the system 'F_{on} _____ by _____'.

b Label the reaction force to the given force using the system 'F_{on} _____ by _____'.

c Draw the reaction force on the diagram, showing its size and location.



The third law and motion

The third law of motion also explains how you are able to move around. In fact, the third law is needed to explain all motion. Consider walking. Your leg pushes backwards on the ground with each step. This is an action force on the ground by the foot. As shown in Figure 7.2.16, a component of the force acts downwards and another component pushes backwards horizontally along the surface of the ground.

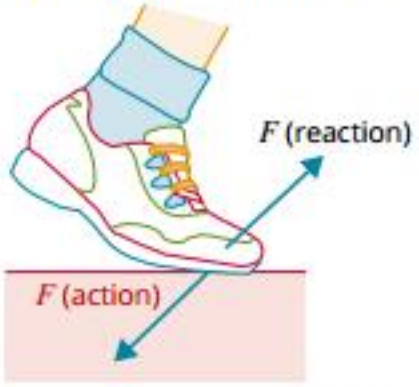


FIGURE 7.2.16 Walking relies on an action–reaction force pair in which the foot pushes down and backwards with an action force. In response, the ground pushes upwards and forwards on you.

The force is transmitted because there is friction between your shoe and the ground. In response, the ground then pushes forwards on you via your foot. This forwards component of the reaction force enables you to move forwards. In other words, it is the ground pushing forwards on you that moves you forwards.

It is important to remember that in the second law, $F_{\text{net}} = ma_{\text{net}}$, the net force, F_{net}, is the sum of the forces acting on the body. This does not include forces that are exerted by the body on other objects. When you push back on the ground, this force is acting on the ground and may affect the ground's motion. If the ground is firm, this effect is usually not noticed, but if you run along a sandy beach, the sand is clearly pushed back by your feet.

The act of walking relies on there being some friction between your shoe and the ground. Without it, there is no grip and it is impossible to supply the action force to the ground. Consequently, the ground cannot supply the reaction force needed to enable forwards motion. Walking on smooth ice is a good example of this. Mountaineers use crampons (basically, a rack of nails) attached to the soles of their boots in order to gain a better grip in icy conditions.

All motion can be explained in terms of action and reaction force pairs. Table 7.2.3 gives some examples of the action and reaction pairs in familiar motions.

TABLE 7.2.3 Action and reaction force pairs are responsible for all types of motion

Motion	Action force	Reaction force
swimming	hand pushes back on water	water pushes forwards on hand
jumping	legs push down on earth	earth pushes up on legs
bicycle or car	tyre pushes back on ground	ground pushes forwards on tyre
rocket	hot gas is forced backwards by the rocket	rocket is forced forwards by the hot gas
skydiving	force of gravitation on the skydiver from earth	force of gravitation on earth from skydiver

FIGURE 7.2.17 When the bin is in mid-air, there is an unbalanced force due to gravity acting on it so it accelerates towards the ground.

The normal force

When an object is allowed to fall under the influence of gravity, it is easy to see the effect of the force due to gravity. Figure 7.2.17 shows a rubbish bin falling to the ground. The action force is the force due to gravity of Earth on the bin. So, the net force on the bin is equal to the force due to gravity; therefore, the bin accelerates at $-9.8\,\text{m}\,\text{s}^{-2}$.

When the bin is at rest on a table, as shown in Figure 7.2.18(a), the force due to gravity ($F_g = mg$) is still acting between the Earth and the bin. The bin is at rest, so there must be another force acting to balance the force due to gravity on the bin. This upwards force is provided by the table. Because gravity pulls down on the mass of the bin, the bottom of the bin will push down on the surface of the table and the table provides a reaction force on the bin that is equal and opposite, so it will push upwards on the bin as shown in Figure 7.2.18(b).

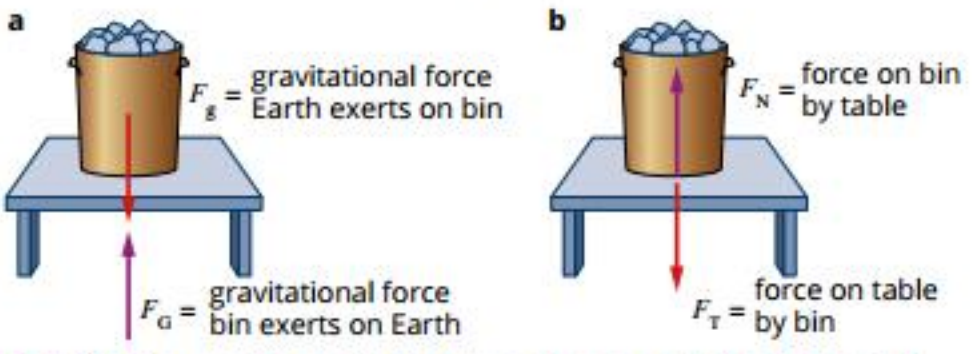

a
F_g = gravitational force Earth exerts on bin
F_G = gravitational force bin exerts on Earth
b
F_N = force on bin by table
F_T = force on table by bin

FIGURE 7.2.18 (a) Action–reaction gravitational forces between the bin and the Earth. (b) Action–reaction contact forces between the bin and the table.

The magnitude and direction of the gravitational force on the bin by Earth is equivalent to the magnitude and direction of the force on the table by the bin. Therefore the gravitational force on the bin by Earth is balanced by the upwards contact reaction force on the bin by the table. But it is important to note that these two forces are not the pair of forces described in the third law of motion. This is because the two forces are both acting on the bin and the third law force pairs all act on *different* objects. The contact force provided by a surface that is perpendicular to another surface is called the normal reaction force. It is often abbreviated to normal force, and represented by F_N or N. The normal reaction force will be discussed in more detail in Units 3 & 4.

7.2 Review

SUMMARY

- The first law of motion states that every object continues to be at rest, or continues with constant velocity, unless it experiences an unbalanced force. This is also called the law of inertia.
- The second law of motion states that the acceleration of a body experiencing an unbalanced force is directly proportional to the net force and inversely proportional to the mass of the body:

$$a_{net} = \frac{F_{net}}{m} \text{ or } F_{net} = ma_{net}$$

- The third law of motion states that when one body exerts a force on another body (an action force), the second body exerts an equal force in the opposite direction on the first (the reaction force): $F_{AB} = -F_{BA}$.
- The forces in an action–reaction pair are the same magnitude, act in opposite directions and are exerted on two different objects.
- For an object on a horizontal surface, the normal reaction force, F_N, and the force due to gravity, F_g, have the same magnitude, but act in opposite directions. When the object is stationary, $F_N = F_g$, and they are not an action–reaction force pair.

KEY QUESTIONS

Describe

1 Complete this sentence describing the first law of motion:
Every object continues to be at rest, or moves with a constant velocity, unless an _____ force acts upon it.

2 State the formula used to calculate net acceleration when applying the second law of motion.

3 Complete this sentence describing the third law of motion: "For every action force there is an _____ and _____ reaction force."

4 State the reaction pair of the normal force ($F_{\text{on person by ground}}$) acting on a person standing on the ground.

Apply

5 A student observes a box sliding across a surface and slowing down to a stop. Discuss the forces acting on the box.

6 Phil was standing inside a tram when it moved off suddenly. Len, who was sitting down, said that Phil was 'thrown backwards' when the tram started to move. Explain, in terms of the laws of motion, whether Len was correct.

7 Identify the forces acting on a hammer and a nail when a heavy hammer hits a small nail.

8 Determine the reaction force involved when a ball is hit with a racquet with a force of 100.0 N west.

9 In the figure below, an astronaut is orbiting the Earth, and one of the forces acting on him is shown by the red arrow.

a Name the given force using the system 'F_{on} _____ by _____'.

b Name the reaction force using the system 'F_{on} _____ by _____'.

Analyse

10 A wheelie bin is wheeled on a straight, horizontal path against a frictional force of 20.0 N at a constant speed of 1.5 m s^{-1}. Calculate the horizontal force that is applied to the wheelie bin.

11 Passengers on commercial flights must be seated with their seatbelts on during take-off and landing. Describe what would happen to a person who was standing in the aisle as the aircraft travelled along the runway during landing.

12 Calculate the acceleration of a 23.9 kg mass when a net force of 158 N north acts on it.

13 Calculate the final velocity of a stationary 3.00 g marble when a net force of 0.0823 N north acts on it for 0.0105 seconds.

14 An astronaut becomes untethered during a spacewalk and drifts away from the spacecraft. To get back to the ship, she decides to throw her tool kit away. Comment on the direction in which she should throw the tool kit.

7.3 Momentum

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the concept of momentum
- find the momentum of an object as the product of its mass and velocity
- understand that changes in momentum are caused by the action of a net force
- solve problems involving momentum.

FIGURE 7.3.1 Momentum is related to mass and velocity. The greater the mass or velocity, the harder it is to stop or start moving.

It is possible to understand some physics concepts intuitively without knowing the physics terms or words that describe them. For example, you may know that once a heavy object gets moving it is difficult to stop it, whereas a lighter object moving at the same speed is easier to stop. In the previous sections of this chapter you have seen how the three laws of motion can be used to explain these observations. In this section you will explore how these observations can be related to the concept called momentum.

The **momentum** of an object relates to both its mass and its velocity. The footballers colliding in Figure 7.3.1 have momentum due to their mass, and the faster they run, the more momentum they will have. A slower moving player has less momentum than one who is moving faster. Similarly, a person with greater mass will have more momentum than a smaller, lighter person travelling at the same speed. The more momentum an object has, due to its mass or its velocity, the more momentum it has to lose before it stops.

The greater an object's mass or velocity, the larger that object's momentum. As velocity is a vector quantity, momentum is also a vector and so it must have magnitude and direction. The direction of a momentum vector will always be the same as the direction of the velocity vector. For calculations of change in momentum in a single dimension, you can use the sign conventions of positive and negative.

The momentum of an object is given by:

$p = mv$

where

p **is momentum (kg m s^{-1})**

m **is the mass of the object (kg)**

v **is the velocity of the object (m s^{-1})**

Momentum is a vector quantity, so it must have magnitude and direction.

Worked example 7.3.1

MOMENTUM

Calculate the momentum of a 60.0 kg student walking at 3.50 m s^{-1} east.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$m = 60.0$ kg $v = 3.50$ m s^{-1} east
Apply the equation for momentum.	$p = mv$ $= 60.0 \times 3.50$ $= 210$ m s^{-1} east

➤ Try yourself 7.3.1

MOMENTUM

Calculate the momentum of a 1230 kg car driving at 16.7 m s^{-1} north.

The change in momentum of an object, Δp, moving in one dimension can be calculated from the mass of the object, m, its initial velocity, u, and its final velocity, v.

$$\Delta p = p_{\text{final}} - p_{\text{initial}}$$
$$= mv - mu$$

The change in momentum of an object is given by:

$\Delta p = mv - mu$

where

Δp **is the change in momentum (kg m s^{-1})**

m **is the mass (kg)**

v **is the final velocity (m s^{-1})**

u **is the initial velocity (m s^{-1})**

Worked example 7.3.2

CHANGE IN MOMENTUM 1

A student rides a bike to school and approaches the bike rack with a velocity of 8.2 m s^{-1} east. The student and the bike have a combined mass of 80 kg and the student stops at the rack.

Calculate the change in momentum of the student during the time it takes to stop.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 80\,\text{kg}$ $u = 8.2\,\text{m s}^{-1}$ east $v = 0\,\text{m s}^{-1}$
Apply the sign convention to the velocity vector.	$m = 80\,\text{kg}$ $u = +8.2\,\text{m s}^{-1}$ $v = 0\,\text{m s}^{-1}$
Apply the equation for change in momentum.	$\Delta p = mv - mu$ $= (80 \times 0) - (80 \times 8.2)$ $= 0 - 656$ $= -6.6 \times 10^2\,\text{kg m s}^{-1}$
Apply the sign convention to describe the direction of the change of momentum.	$\Delta p = 6.6 \times 10^2\,\text{kg m s}^{-1}$ west

➤ Try yourself 7.3.2

CHANGE IN MOMENTUM 1

A student hurries to class after lunch, moving with a velocity of 4.55 m s^{-1} north. She suddenly remembers that she has forgotten her laptop and goes back to her locker at a velocity of 6.15 m s^{-1} south. If her mass is 75.0 kg, calculate the change in momentum of the student during the time it takes to turn around.

Worked example 7.3.3

CHANGE IN MOMENTUM 2

A car of mass 1500 kg that is initially travelling at 30.0 m s^{-1} north undergoes a change of momentum of 12000 kg m s^{-1} south. Calculate the final velocity of the car.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$m = 1500\,\text{kg}$ $u = 30.0\,\text{m s}^{-1}$ north $\Delta p = 12000\,\text{kg m s}^{-1}$ south
Apply the sign convention to the velocity vector.	$m = 1500\,\text{kg}$ $u = +30.0\,\text{m s}^{-1}$ $\Delta p = -12000\,\text{kg m s}^{-1}$
Apply the equation for change in momentum.	$\Delta p = mv - mu$ $-12000 = (1500 \times v) - (1500 \times 30.0)$ $-12000 = 1500v - 45000$ $33000 = 1500v$ $v = +\frac{33\,000}{1500}$ $= +22.0\,\text{m s}^{-1}$
Apply the sign convention to describe the direction of the change of momentum.	$v = 22.0\,\text{m s}^{-1}$ north

➤ Try yourself 7.3.3

CHANGE IN MOMENTUM 2

A 2200 kg elephant walking at 2.5 m s^{-1} north suddenly undergoes a change of momentum of 4400 kg m s^{-1} north. Calculate the final velocity of the elephant.

Force is equal to the rate of change of momentum. This can be shown using the second law of motion, $a_{net} = \frac{F_{net}}{m}$, and the acceleration equation $a = \frac{v - u}{\Delta t}$.

The following derivation shows how the second law relates to momentum. It results with net force, F_{net}, equal to the change in momentum, Δp, divided by the period of time, Δt, which is the rate of change of momentum:

$$\begin{aligned} a_{net} &= \frac{F_{net}}{m} \\ F_{net} &= ma_{net} \\ &= m\frac{(v - u)}{\Delta t} \\ &= \frac{mv - mu}{\Delta t} \\ &= \frac{\Delta p}{\Delta t} \end{aligned}$$

This means that changes in momentum are caused by the action of a net force.

The second law showed that when forces act on an object, a change of momentum occurs. When an object changes its velocity, its momentum will also change. An increase in velocity corresponds to an increase in momentum, and a decrease in velocity corresponds to a decrease in momentum. This change often occurs in collisions, so you can also consider this change in momentum as a transfer of momentum.

It is easy to change the velocity of an object. You can either run faster or run slower; you can press a little harder on the pedals of a bike or press a little softer. You can also bounce an object off a surface. For example, the basketball in Figure 7.3.2 experiences a change in velocity when it changes direction during the bounce. The cause of these changes in motion will be discussed in Module 7.4.

FIGURE 7.3.2 A bouncing basketball undergoes a change in momentum when it changes direction as it bounces.

7.3 Review

SUMMARY

- Momentum is the product of an object's mass and velocity.
- Momentum is a vector quantity and is calculated using the equation $p = mv$.
- Change or transfer in momentum, Δp, is also a vector quantity, and is given by $\Delta p = mv - mu$.
- A change or transfer in momentum occurs when an object changes its velocity; that is, when it accelerates or has a net force acting on it.

KEY QUESTIONS

Describe

1 State the two properties of an object that are used to calculate its momentum.

2 Recall the SI unit for momentum.

3 Give an equation for:

a the momentum of an object in terms of mass and velocity

b the change in momentum of an object in terms of mass, initial velocity and final velocity.

4 Complete this sentence describing the behaviour of momentum in collisions:

An object at rest may experience a change in velocity when it collides with an object in motion, as the object in motion _____ its momentum to the object at rest.

Apply

5 Viggo runs south at $5\,km\,h^{-1}$, then turns around and runs north at $5\,km\,h^{-1}$. He says that because his speed is the same, his momentum has not changed. Explain why he is not correct.

6 Describe the momentum of a car when its velocity is halved. (Assume its mass remains constant).

7 Describe the momentum of a car as it slows down to a stop. (Assume its mass stays constant).

Analyse

8 Calculate the momentum of a 3.50 kg fish swimming at $2.50\,m\,s^{-1}$ south.

9 Determine which of these objects has the greatest momentum:

- a medicine ball of mass 4.5 kg travelling at $3.5\,m\,s^{-1}$
- a medicine ball of mass 2.5 kg travelling at $6.8\,m\,s^{-1}$.

10 Calculate the change in momentum of a 9.50 kg dog that changes its velocity from $2.50\,m\,s^{-1}$ north to $6.25\,m\,s^{-1}$ south.

11 The momentum of a ball of mass 0.125 kg changes by $0.075\,kg\,m\,s^{-1}$ south. If its original velocity was $3.00\,m\,s^{-1}$ north, determine its final velocity.

7.4 Impulse

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe impulse as the change in momentum of an object
- calculate the impulse and force acting on an object
- calculate the impulse from a force–time graph
- solve problems involving momentum, impulse, the conservation of momentum and collisions in one dimension.

IMPULSE OF A FORCE

In a car crash, it is not only the speed of the car that counts, it is also how quickly it stops!

This is a direct consequence of the second law of motion. If the velocity decreases over a long time, the deceleration is small. Using the formula $F = ma$, if a is small, you can conclude that the force required to bring the car to a stop will also be relatively small. If, however, the car is brought to a halt very rapidly, there will be a large deceleration requiring a large force (Figure 7.4.1). The force determines the damage. Despite the likelihood of injury caused by a large force that acts for a short time, such as in a car crash, a smaller force acting for a longer time has the same effect on the motion of an object. Gradually applying the brakes will also bring the car to rest. One way to quantify the similarity between these situations is to describe the impulse in a **collision**, which considers both the force and the time over which the force acts.

FIGURE 7.4.1 Rapid deceleration requires a large force and often results in damage and injury.

An **impulse** is a measure of the force on a body and the time over which the force acts. An impulse is calculated as the product of the resultant force, F_{net} (often just written as F), and the change in time, Δt.

$$I = F_{net}\Delta t$$

From the second law of motion, $F_{net} = \frac{\Delta p}{\Delta t}$, it can be shown that:

$$I = F_{net}\Delta t = \Delta p$$

From the change in momentum equation, $\Delta p = mv - mu$, it can be shown that:

$$I = \Delta p = mv - mu$$

The impulse, I, of the resultant force is equal to the change in momentum of the object. Impulse is a vector quantity, and so requires direction as well as magnitude. Its units are newton seconds (N s).

The impulse of the resultant force acting on an object is given by:

$I = F_{net}\Delta t = \Delta p = mv - mu$

where

- I is the impulse (N s)
- F_{net} is the net force (N)
- t is the time (s)
- Δp is the change in momentum (kg m s^{-1})
- m is the mass (kg)
- v is the final velocity (m s^{-1})
- u is the initial velocity (m s^{-1})

Units of momentum

Impulse can be expressed in terms of a momentum change, so the units for momentum ($kg\,m\,s^{-1}$) and impulse ($N\,s$) must be equivalent. This can be shown by using the second law of motion.

Given that $1\,N = 1\,kg\,m\,s^{-2}$ (from $F = ma$), it follows that $1\,N\,s = 1\,kg\,m\,s^{-2} \times s$

$$1\,N\,s = 1\,kg\,m\,s^{-1}$$

Even though the units are equivalent, they should be used with the appropriate quantity that is involved.

The newton second ($N\,s$) is the product of a force and a time interval and so should be used with impulse. The kilogram metre per second ($kg\,m\,s^{-1}$) is the product of a mass and a velocity and so should be used with momentum. Even so, it is not uncommon to see newton seconds used as the unit of momentum, nor is this incorrect.

Worked example 7.4.1

CALCULATING THE IMPULSE AND FORCE

A 1485 kg sports car is travelling at $93.0\,km\,h^{-1}$ north when the driver loses control of the car on an icy road. The car comes to rest against a tree.

a Calculate the impulse of the tree on the car.

Thinking	Working
Convert $km\,h^{-1}$ to $m\,s^{-1}$.	$93.0\,km\,h^{-1} = \frac{93.0}{3.6}\,m\,s^{-1} = 25.8\,m\,s^{-1}$
Calculate the change in momentum. The negative sign indicates that the change in momentum (the impulse), is in the direction opposite to the car's initial momentum, as would be expected.	$\Delta p = mv - mu$ $= (1485 \times 0) - (1485 \times 25.8)$ $= 0 - 38313$ $= -383 \times 10^4\,kg\,m\,s^{-1}$
The impulse is the change in momentum of the car. Apply a sign convention to the answer, taking north as positive, and remember to give the units as N s.	$I = 3.84 \times 10^4\,N\,s$ south

b If the car crumples in 40.0 ms, find the force exerted by the tree on the car.

Thinking	Working
Transpose $\Delta p = F_{net}\,\Delta t$ to find the force.	$F_{net} = \frac{\Delta p}{\Delta t}$ $= \frac{-3.84 \times 10^4}{40.0 \times 10^{-3}}$ $= -9.59 \times 10^5\,N$ $= 9.59 \times 10^5\,N$ south

➤ Try yourself 7.4.1

CALCULATING THE IMPULSE AND FORCE

The driver of a 1485 kg car stops to refuel. The vehicle was travelling at $95.5\,km\,h^{-1}$ north and took 12.5 s to come to a halt at the petrol station.

a Calculate the impulse of the braking system on the car.

b Calculate the average braking force.

Worked example 7.4.2

CALCULATING THE FORCE AND IMPULSE

A student drops a 105 g pool ball onto a concrete floor from a height of 2.00 m. Just before it hits the floor, the velocity of the ball is 6.26 m s^{-1} down. Before it bounces back up, there is an instant in time at which the ball's velocity is zero. The time it takes for the ball to change its velocity to zero is 5.02 ms.

a Calculate the change in momentum of the pool ball.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 0.105\,\text{kg}$ $u = 6.26\,\text{m s}^{-1}$ down $v = 0\,\text{m s}^{-1}$
Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	$m = 0.105\,\text{kg}$ $u = -6.26\,\text{m s}^{-1}$ $v = 0\,\text{m s}^{-1}$
Apply the equation for change in momentum.	$\Delta p = mv - mu$ $= (0.105 \times 0) - (0.105 \times -6.26)$ $= 0.657\,\text{kg m s}^{-1}$
Refer to the sign and direction convention to determine the direction of the change in momentum.	$\Delta p = 0.657\,\text{kg m s}^{-1}$ up

b Calculate the impulse of the pool ball.

Thinking	Working
Using the answer to part (a), apply the equation for impulse.	$I = \Delta p$ $= 0.657\,\text{N s}$
Refer to the sign and direction convention to determine the direction of the impulse.	$I = 0.657\,\text{N s}$ up

c Calculate the force that acts to cause the impulse.

Thinking	Working
Use the answer to part (b). Ensure that the variables are in their standard units. $5.02\,\text{ms} = 5.02 \times 10^{-3}\,\text{s}$	$I = 0.657\,\text{N s}$ $\Delta t = 5.02 \times 10^{-3}\,\text{s}$
Apply the equation for force.	$F\Delta t = I$ $F = \frac{I}{\Delta t}$ $= \frac{0.657}{5.02 \times 10^{-3}}$ $= 131\,\text{N}$
Refer to the sign and direction convention to determine the direction of the force.	$F = 131\,\text{N}$ up

➤ Try yourself 7.4.2

CALCULATING THE FORCE AND IMPULSE

A student drops a 56.0 g egg onto a table from a height of 60.0 cm. Just before it hits the table, the velocity of the egg is 3.43 m s^{-1} down. The egg's final velocity is zero as it smashes on the table. The time it takes for the egg to change its velocity to zero is 3.55 ms.

a Calculate the change in momentum of the egg.

b Calculate the impulse of the egg.

c Calculate the force that acts to cause the impulse.

Worked example 7.4.3

CALCULATING THE FORCE AND IMPULSE (SOFT LANDING)

A student drops a 105 g pool ball onto a foam mattress from a height of 2.00 m. Just before it hits the foam mattress, the velocity of the ball is 6.26 m s^{-1} down. Before it bounces back up, there is an instant in time at which the ball's velocity is zero. The time it takes for the ball to change its velocity to zero is 0.360 s.

a Calculate the change in momentum of the pool ball.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 0.105\,\text{kg}$ $u = 6.26\,\text{m s}^{-1}$ down $v = 0\,\text{m s}^{-1}$
Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	$m = 0.105\,\text{kg}$ $u = -6.26\,\text{m s}^{-1}$ $v = 0\,\text{m s}^{-1}$
Apply the equation for change in momentum.	$\Delta p = mv - mu$ $= (0.105 \times 0) - (0.105 \times -6.26)$ $= 0.657\,\text{kg m s}^{-1}$
Refer to the sign and direction convention to determine the direction of the change in momentum.	$\Delta p = 0.657\,\text{kg m s}^{-1}$ up

b Calculate the impulse of the pool ball.

Thinking	Working
Using the answer to part (a), apply the equation for impulse.	$I = \Delta p$ $= 0.657\,\text{N s}$
Refer to the sign and direction convention to determine the direction of the impulse.	$I = 0.657\,\text{N s}$ up

c Calculate the force that acts to cause the impulse.

Thinking	Working
Using the answer to part (b), ensure that the variables are in their standard units.	$I = 0.657\,\text{N s}$ $\Delta t = 0.360\,\text{s}$
Apply the equation for force.	$F\Delta t = I$ $F = \frac{I}{t}$ $= \frac{0.657}{0.360}$ $= 1.83\,\text{N}$
Refer to the sign and direction convention to determine the direction of the force.	$F = 1.83\,\text{N}$ up

➤ Try yourself 7.4.3

CALCULATING THE FORCE AND IMPULSE (SOFT LANDING)

A student drops a 56.0 g egg into a mound of flour from a height of 60.0 cm. Just before it hits the mound of flour, the velocity of the egg is 3.43 m s^{-1} down. The egg's final velocity is zero as it sinks into the mound of flour. The time it takes for the egg to change its velocity to zero is 0.325 seconds.

a Calculate the change in momentum of the egg.

b Calculate the impulse of the egg.

c Calculate the force that acts to cause the impulse.

b

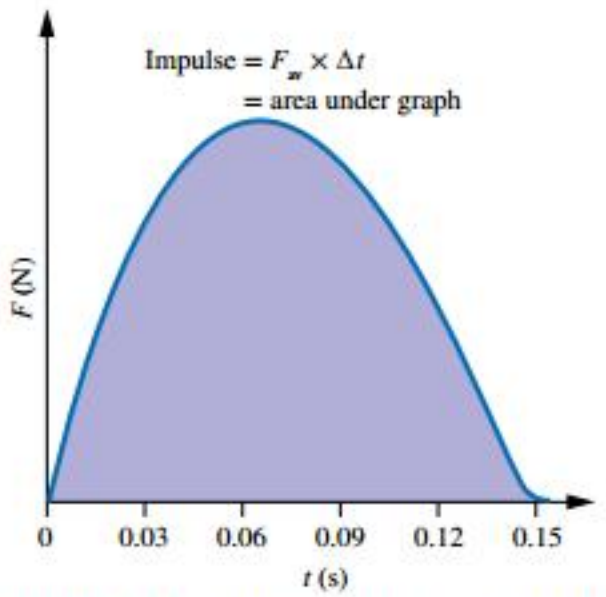


FIGURE 7.4.2 (a) The tennis player hits the ball with a racquet. (b) The force changes with time as the racquet strikes the ball.

From these worked examples you should notice that:

- the change in momentum and the impulse were always the same
- regardless of the surface that the object landed on, the impulse or change in momentum remained the same
- the period of time was the main difference between the two surfaces; hard surfaces resulted in a shorter time to stop than soft surfaces
- the effect of the period of time on the force was dramatic; the shorter the time, the greater the force.

FORCE–TIME GRAPHS

In many practical applications, the force applied to an object is not constant. For example, when a tennis player hits a ball, the initial force exerted by the racquet is relatively small. As the strings stretch and the ball deforms, this force builds up to a maximum value before decreasing again as the ball rebounds from the racquet. If the force is measured over time, this data can be represented graphically (Figure 7.4.2).

The impulse of the ball, or the change in momentum, may be found from the product of the average force, F_{av}, and time, Δt:

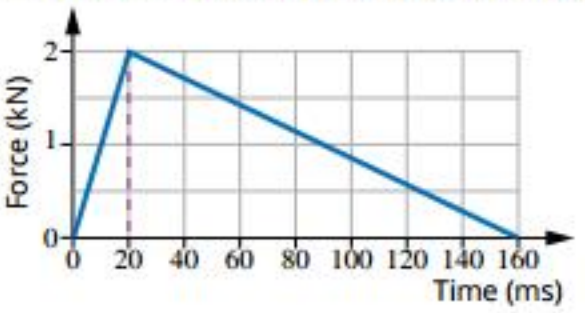
$$I = F_{av}\Delta t$$

Impulse is simply the area under the force–time graph.

Worked example 7.4.4

RUNNING SHOES

A running-shoe company plots the following force–time graph for a running shoe. Use the data to calculate the magnitude of the impulse.

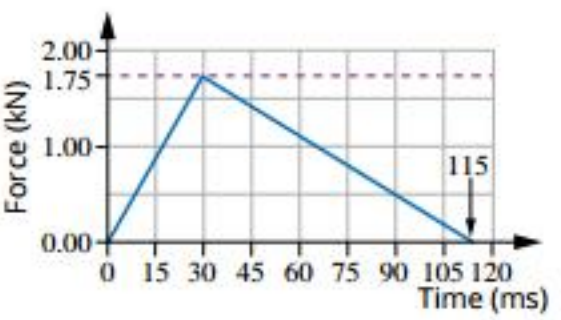


Thinking	Working
Recall that impulse $I = F_{av}\Delta t$. When the force is not constant, impulse is the area under the force–time graph. The area shown is a triangle.	$I = \frac{b \times h}{2}$ $= \frac{(160 \times 10^{-3}) \times (2 \times 10^{3})}{2}$ $= 160$ N s

➤ Try yourself 7.4.4

RUNNING SHOES

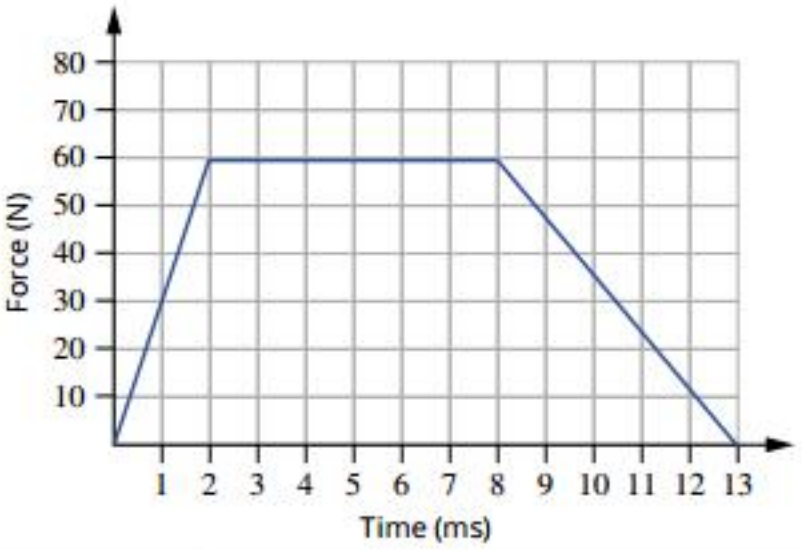
A running-shoe company plots the following force–time graph for an alternative design intended to reduce the peak force on the heel. Calculate the magnitude of the impulse.



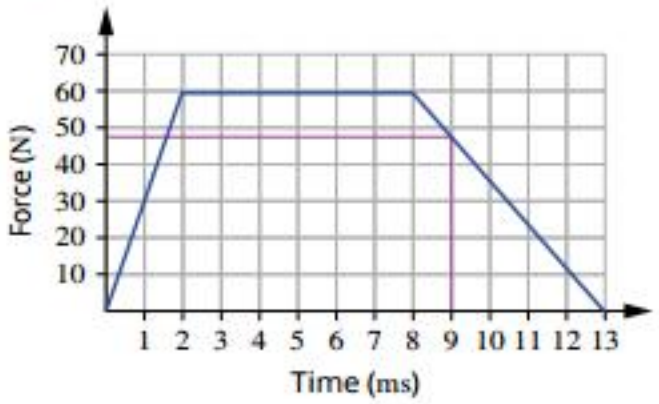
Worked example 7.4.5

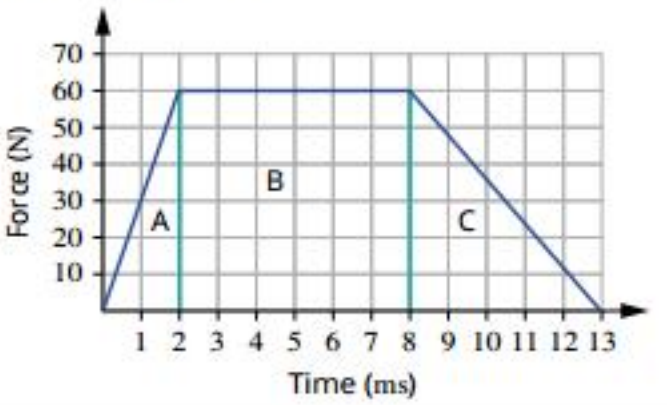
CALCULATING THE TOTAL IMPULSE FROM A CHANGING FORCE

A student records the force acting on a rubber ball as it bounces off a hard concrete floor over a period of time. The graph shows the forces acting on the ball during its collision with the concrete floor.



a Determine the force acting on the ball over a time of 9.0 ms.

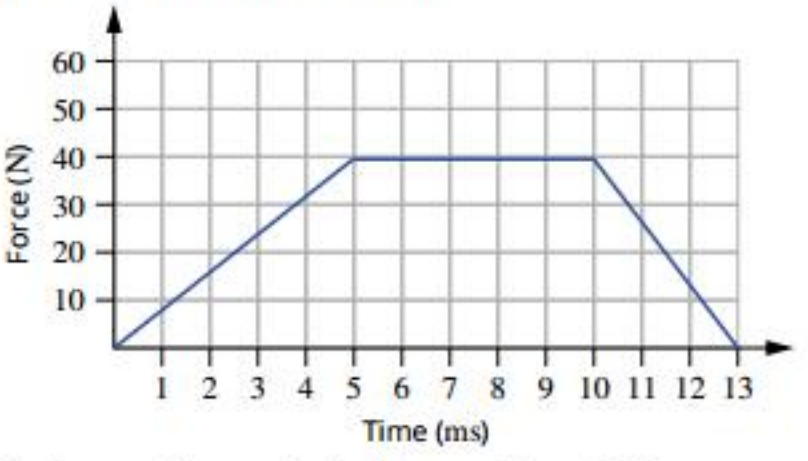
Thinking	Working
From the 9.0 ms point on the horizontal axis, go up to the line of the graph, then across to the vertical axis.	
The force is estimated by reading the intercept of the vertical axis.	$F = 48\,\text{N}$

b Calculate the total impulse of the ball over the 13 ms period of time.	
Thinking	**Working**
Break the area under the graph into sections for which you can calculate the area.	In this case, the graph can be broken into three sections: A, B and C. 
Calculate the area of the three sections A, B and C using the equations for area of a triangle and the area of a rectangle.	area = area A + area B + area C $= \left(\frac{1}{2}b \times h\right) + (b \times h) + \left(\frac{1}{2}b \times h\right)$ $= \left(\frac{1}{2} \times (2 \times 10^{-3}) \times 60\right) + \left((6 \times 10^{-3}) \times 60\right)$ $+ \left(\frac{1}{2} \times (5 \times 10^{-3}) \times 60\right)$ $= 0.06 + 0.36 + 0.15$ $= 0.57 = 0.6$
The total impulse is equal to the area.	$I = 0.6$ N s
Apply the sign and direction convention for motion in one dimension vertically.	$I = 0.6$ N s up

➤ Try yourself 7.4.5

CALCULATING THE TOTAL IMPULSE FROM A CHANGING FORCE

A student records the force acting on a tennis ball as it bounces off a hard concrete floor over a period of time. The graph shows the forces acting on the ball during its collision with the concrete floor.



a Determine the force acting on the ball over a time of 4.0 ms.

b Calculate the total impulse of the ball over the 13 ms period of time.

7.4 Review

SUMMARY

- The change in momentum of an object with a net force acting on it is known as the impulse, I.
- Impulse, $I = F_{net}\Delta t = mv - mu = \Delta p$
- The units for impulse are N s, and for a change in momentum are kg m s^{-1}. These units are equivalent.
- Impulse can be calculated from the area under a force–time graph.
- In many practical applications, measures are taken to increase the time of the interaction to reduce the maximum force.
- Often the force applied to an object is not constant. The impulse of the ball in this case may be found from the product of the average force, F_{av}, and time, Δt.

KEY QUESTIONS

Describe

1 State an equation for the impulse acting on an object in terms of:
- **a** the mass, and initial and final velocity of the object
- **b** the resultant force acting and the time over which the force acts.

2 State the units for:
- **a** change in momentum **b** impulse.

3 State an equation for the net force acting on an object in terms of:
- **a** the impulse and time over which the force acts
- **b** the mass, initial velocity, and final velocity of the object and time over which the force acts.

Apply

4 Explain why a man fielding in a cricket match cups his hands and then draws them into his body as the ball reaches his hands.

5 Crash helmets have a hard outside layer and foam padding inside. Explain the function of foam padding inside a helmet.

6 Air-injected rubber—which is more flexible than traditional rubber—is often used in running shoes. A student forgets their running shoes and must complete running trials in their dress shoes, which have a firm rubber sole. Compare and explain the effect that the dress shoes and running shoes will have on the forces experienced by the student.

Analyse

7 The velocity of an 8.00 kg mass changes from 3.00 m s^{-1} east to 8.00 m s^{-1} east. Calculate the impulse acting on the mass.

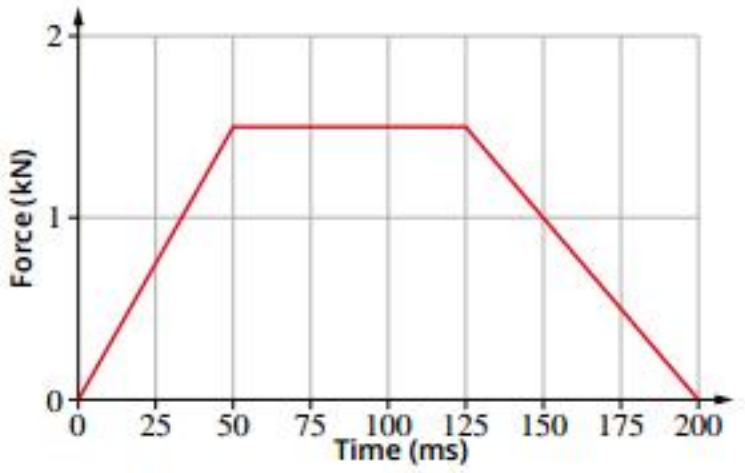
8 When a tennis player serves, she hits the 57 g tennis ball at the top if its flight so that the ball is momentarily stationary and leaves the racquet at 144 km h^{-1}. If the ball and racquet are in contact for 0.060 s, calculate the magnitude of the force exerted by the racquet on the ball.

9 A basketball of mass 0.625 kg is bounced against the court at a speed of 32.0 m s^{-1} and it rebounds at 24.5 m s^{-1}. Calculate the force exerted by the court on the ball if the interaction lasts 16.5 ms.

10 Jacinta inflates two basketballs to different pressures and drops them from the same height. The ball with the higher pressure bounces higher. She argues that, if each of the two balls were thrown with the same speed at a player, the ball with greater pressure would hurt more. Sarah disagrees, arguing that the balls have essentially the same mass and speed, and so there will not be any difference when they hit the player. Determine who is correct and justify your answer.

*The following information relates to questions **11–12**.*

The force–time graph below shows a schematic representation of the force exerted by an athlete's foot when running in shoes with a flexible sole.



11 Determine the force experienced by the athlete at 50 ms.

12 Calculate the magnitude of the impulse of the athlete on the ground.

7.5 Conservation of momentum

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that momentum is conserved in all collisions
- understand mathematically how momentum is conserved when masses combine, and in explosions
- describe the principle of conservation of momentum
- solve problems using the principle of conservation of momentum.

The most significant feature of momentum is that it is **conserved** in any interaction or collision between objects. This means that the total (sum of) momentum in any system before a collision will be equal to the total (sum of) momentum in the system after the collision. This is known as the law of conservation of momentum and can be represented by the following relationship, where Σp is the sum of the momentum of objects in a system.

$$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$$

To find the total momentum of objects in a system (either before or after a collision), simply find the momentum of each object, considering their masses and velocities, and then add the momenta together.

For collisions in one dimension, apply the sign convention of positive and negative directions to the velocities and then use algebra to determine the answer to the problem.

THE THIRD LAW OF MOTION AND MOMENTUM

This law of conservation of momentum is a direct consequence of applying the third law of motion to a situation in which two objects come together in a collision or move apart in an **explosion**. If the words collision or explosion appear in a question, they are signposts that you should consider the conservation of momentum.

Remember, the third law states that for every action force, there is an equal and opposite reaction force. This means that when object 1 exerts a force, F_{21}, on object 2, object 2 will exert an equal and opposite force, $-F_{12}$, on object 1. Remember that F_{12} is the same as writing $F_{\text{on 1 by 2}}$. You can write this mathematically as:

$$F_{12} = -F_{21}$$

In a collision between two objects, the time of contact, t, is the same for both objects.

$$F_{12}\Delta t = -F_{21}\Delta t$$

You will recognise this as the equation for impulse from Module 7.4, where $\Delta p = F\Delta t$. In a collision, the third law can be thought of in terms of equal and opposite impulses, or the change in momentum of object 1 must be equal and opposite to the change in momentum of object 2.

$$F_{12}\Delta t = -F_{21}\Delta t$$
$$\Delta p_1 = -\Delta p_2$$

Given that $p = mv$:

$$m_1v_1 - m_1u_1 = -(m_2v_2 - m_2u_2)$$

This can be rearranged as:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

In other words, the total momentum before is equal to the total momentum after:

$$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$$

The law of conservation of momentum is a direct result of the laws of motion.

If two objects collide in one dimension, then:

$\Sigma p_{before} = \Sigma p_{after}$

$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$

where

m_1 is the mass of object 1 (kg)
m_2 is the mass of object 2 (kg)
u_1 is the initial velocity of object 1 ($m\,s^{-1}$)
u_2 is the initial velocity of object 2 ($m\,s^{-1}$)
v_1 is the final velocity of object 1 ($m\,s^{-1}$)
v_2 is the final velocity of object 2 ($m\,s^{-1}$)

Worked example 7.5.1

CONSERVATION OF MOMENTUM

A 2.50 kg mass is moving at 4.50 $m\,s^{-1}$ west towards a 1.50 kg mass moving at 3.00 $m\,s^{-1}$ east. Calculate the final velocity of the 2.50 kg mass if the 1.50 kg mass rebounds at 5.00 $m\,s^{-1}$ west.

Thinking	Working
Identify the variables using subscripts. Ensure that the variables are in their standard units.	$m_1 = 2.50\,kg$ $u_1 = 4.50\,m\,s^{-1}$ west $v_1 = ?$ $m_2 = 1.50\,kg$ $u_2 = 3.00\,m\,s^{-1}$ east $v_2 = 5.00\,m\,s^{-1}$ west
Apply the sign convention to the variables, using east as positive.	$m_1 = 2.50\,kg$ $u_1 = -4.50\,m\,s^{-1}$ $v_1 = ?$ $m_2 = 1.50\,kg$ $u_2 = +3.00\,m\,s^{-1}$ $v_2 = -5.00\,m\,s^{-1}$
Apply the equation for conservation of momentum.	$\Sigma p_{before} = \Sigma p_{after}$ $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$ $(2.50 \times -4.50) + (1.50 \times 3.00) = 2.50v_1 + (1.50 \times -5.00)$ $2.50v_1 = -11.25 + 4.50 - (-7.50)$ $v_1 = \frac{0.75}{2.50}$ $= 0.300\,m\,s^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$v_1 = 0.300\,m\,s^{-1}$ east

Try yourself 7.5.1

CONSERVATION OF MOMENTUM

A 1200 kg wrecking ball is moving at 2.50 $m\,s^{-1}$ north towards a 1500 kg wrecking ball moving at 4.00 $m\,s^{-1}$ south. Calculate the final velocity of the 1500 kg ball if the 1200 kg ball rebounds at 3.50 $m\,s^{-1}$ south.

MOMENTUM WHEN MASSES COMBINE

It is important to note that in the situations described in Worked example 7.5.1, the two objects remain separate from each other. However, it is possible for two objects to combine (stick together) when they collide. If two objects combine when they collide, momentum is still conserved: $\Sigma p_{before} = \Sigma p_{after}$.

$\Sigma p_{before} = \Sigma p_{after}$

$m_1u_1 + m_2u_2 = m_3v_3$

where

- m_1 is the mass of object 1 (kg)
- m_2 is the mass of object 2 (kg)
- m_3 is the combined mass of objects 1 and 2 (kg)
- u_1 is the initial velocity of object 1 ($m\,s^{-1}$)
- u_2 is the initial velocity of object 2 ($m\,s^{-1}$)
- v_3 is the final velocity of the combined objects 1 and 2 ($m\,s^{-1}$)

Worked example 7.5.2

CONSERVATION OF MOMENTUM WHEN MASSES COMBINE

A 5.00 kg lump of clay is moving at 2.00 $m\,s^{-1}$ west towards a 7.50 kg mass of clay moving at 3.00 $m\,s^{-1}$ east. They collide to form a single, combined mass of clay. Calculate the final velocity of the combined mass of clay.

Thinking	Working
Identify the variables using subscripts and ensure that the variables are in their standard units. Add m_1 and m_2 to get m_3.	$m_1 = 5.00\,kg$ $u_1 = 2.00\,m\,s^{-1}$ west $m_2 = 7.50\,kg$ $u_2 = 3.00\,m\,s^{-1}$ east $m_3 = 12.50\,kg$ $v_3 = ?$
Apply the sign convention to the variables, using east as positive.	$m_1 = 5.00\,kg$ $u_1 = -2.00\,m\,s^{-1}$ $m_2 = 7.50\,kg$ $u_2 = +3.00\,m\,s^{-1}$ $m_3 = 12.50\,kg$ $v_3 = ?$
Apply the equation for conservation of momentum.	$\Sigma p_{before} = \Sigma p_{after}$ $m_1u_1 + m_2u_2 = m_3v_3$ $(5.00 \times -2.00) + (7.50 \times 3.00) = 12.50v_3$ $v_3 = \frac{-10.0 + 22.50}{12.50}$ $= 1.00\,m\,s^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$v_3 = 1.00\,m\,s^{-1}$ east

➤ Try yourself 7.5.2

CONSERVATION OF MOMENTUM WHEN MASSES COMBINE

An 80.0 kg rugby player is moving at 1.50 $m\,s^{-1}$ north when he tackles an opponent with a mass of 50.0 kg who is moving at 5.00 $m\,s^{-1}$ south. Calculate the final velocity of the two players during the tackle.

MOMENTUM IN EXPLOSIONS

It is also possible for one object to break apart into two objects in what is known as an explosion. If an object breaks apart in an explosion, momentum is still conserved:

$$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$$

$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$

$m_1 u_1 = m_2 v_2 + m_3 v_3$

where

- m_1 is the mass of object 1 (kg)
- m_2 is the mass of object 2 (kg)
- m_3 is the mass of object 3 (kg)
- u_1 is the initial velocity of object 1 ($m s^{-1}$)
- v_2 is the final velocity of object 2 ($m s^{-1}$)
- v_3 is the final velocity of object 3 ($m s^{-1}$)

Worked example 7.5.3

CONSERVATION OF MOMENTUM FOR EXPLOSIVE COLLISIONS

A 90.0 kg athlete holds a 1000.0 g javelin. She approaches the line at 7.75 $m s^{-1}$ west and releases the javelin down the field. After throwing it, she continues with a velocity of 7.25 $m s^{-1}$ west.

a Calculate the velocity of the javelin just after she releases it.

Thinking	Working
Identify the variables using subscripts and ensure that the variables are in their standard units. Note that m_1 is the sum of the bodies: 90.0 kg athlete and 1.00 kg javelin.	$m_1 = 91.0\,kg$ $u_1 = 7.75\,m s^{-1}$ west $m_2 = 90.0\,kg$ $v_2 = 7.25\,m s^{-1}$ west $m_3 = 1.00\,kg$ $v_3 = ?$
Apply the sign convention to the variables, using east as positive.	$m_1 = 91.0\,kg$ $u_1 = -7.75\,m s^{-1}$ $m_2 = 90.0\,kg$ $v_2 = -7.25\,m s^{-1}$ $m_3 = 1.00\,kg$ $v_3 = ?$
Apply the equation for conservation of momentum for explosive collisions.	$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$ $m_1 u_1 = m_2 v_2 + m_3 v_3$ $91.0 \times -7.75 = (90.0 \times -7.25) + 1.00 v_3$ $v_3 = \frac{-705.25 - (-652.5)}{1.00}$ $v_3 = \frac{-52.75}{1.00}$ $= -52.8\,m s^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$v_3 = 52.8\,m s^{-1}$ west

b With reference to the conservation of momentum for explosive collisions, contrast the change in velocities of the athlete and the javelin after it is thrown.

Thinking	Working
Calculate the change in velocities of the athlete and the javelin.	$\Delta v_{athlete} = -7.25 - (-7.55)$ $= 0.30\,m\,s^{-1}$ east $\Delta v_{javelin} = -52.75 - (-7.55)$ $= 45.2\,m\,s^{-1}$ west
Identify any differences between the direction and magnitude of the velocities of the athlete and the javelin.	The direction of the change in velocity of the javelin after it is thrown is opposite to the direction of the change in velocity of the athlete. The magnitude of the change in velocity of the javelin is significantly greater than the magnitude of the change in velocity of the athlete.
Apply the conservation of momentum for explosive collisions to contrast the direction and magnitude of the athlete and the javelin.	The momentum before the explosive collision is a product of the combined mass of the athlete and the javelin. As expected of the conservation of momentum for explosive collisions, the direction of the change in velocity of the two objects is opposite in direction. As the momentum after the explosive collision is conserved, the greater mass of the athlete means they have a smaller change in velocity than the javelin.

➤ Try yourself 7.5.3

CONSERVATION OF MOMENTUM FOR EXPLOSIVE COLLISIONS

A 2000.0 kg cannon fires a 10.0 kg cannonball. The cannon and the cannonball are initially stationary. After firing, the cannon recoils with a velocity of $8.15\,m\,s^{-1}$ north.

a Calculate the velocity of the cannonball just after it is fired.

b With reference to the conservation of momentum for explosive collisions, contrast the change in velocities of the cannon and the cannonball after it is fired.

7.5 Review

SUMMARY

- Momentum is conserved in all collisions.
- The law of conservation of momentum can be applied to situations in which:
  - two objects collide and remain separate:

$$\Sigma p_{before} = \Sigma p_{after}$$

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

  - two objects collide and combine together:

$$\Sigma p_{before} = \Sigma p_{after}$$

$$m_1u_1 + m_2u_2 = m_3v_3$$

  - one object breaks apart into two objects in an explosion:

$$\Sigma p_{before} = \Sigma p_{after}$$

$$m_1u_1 = m_2v_2 + m_3v_3$$

KEY QUESTIONS

Describe

1 State the equation for the conservation of momentum.

2 Give an equation for the conservation of momentum, in terms of mass and velocity, when:
- **a** two objects collide and remain separate
- **b** two objects collide and stick together
- **c** one object breaks apart into two objects.

3 Describe the principle of conservation of momentum when applied to collisions.

Apply

4 In a game of pool, the white ball is hit and collides with the black ball. After the collision, the balls travel off in different directions. Describe the magnitude of the velocity of the balls before and after the collision with reference to the conservation of momentum.

5 A car in motion collides with another car at rest. The two cars travel forwards some distance with their bumpers connected. Describe the motion of the cars before and after the collision with reference to the conservation of momentum.

6 Two students are sitting on chairs with wheels, opposite each other. One student pushes the other and they both roll backwards. Describe the motion of the students before and after the collision with reference to the conservation of momentum.

Analyse

7 A golf ball of mass 48 g is stationary on the ground. It is hit by a 750 g golf club. If the velocity of the club immediately after the collision is $75\,m\,s^{-1}$, and the ball leaves the club at a speed of $80.6\,m\,s^{-1}$, determine the momentum of the club just before it hits the ball.

8 When playing roller derby, Ali is moving at $3.0\,m\,s^{-1}$. She barges into another player who is moving at $0.50\,m\,s^{-1}$. If the two players move off locked together, and the mass of each player is 65.0 kg, calculate their final velocity.

9 A space shuttle of mass 10 000.0 kg is at rest. The shuttle burns 5.0 kg of fuel to eject exhaust gases downwards at a velocity of $6000.0\,m\,s^{-1}$. Calculate the new velocity of the space shuttle.

Chapter review

07

KEY TERMS

collision
conserved
contact forces
equilibrium
explosion
first law of motion
force
impulse
inertia
momentum
net force
non-contact forces
resultant force
second law of motion
third law of motion

KEY QUESTIONS

Describe

1 Match the statements **a–g** with the law of motion—first, second or third—that they correspond to.

a The acceleration of a body experiencing an unbalanced force is directly proportional to the net force and inversely proportional to the mass of the body.

b Every object continues to be at rest, or continues with constant velocity, unless it experiences an unbalanced force.

c When one body exerts a force on another body (an action force), the second body exerts an equal force in the opposite direction on the first (the reaction force).

d $F_{AB} = -F_{BA}$

e $F_{net} = ma_{net}$

f the law of inertia

g $a_{net} = \frac{F_{net}}{m}$

2 If the acceleration of an object is doubled, state whether the net force has increased or decreased.

3 The conservation of momentum in an interaction is given by the equation $m_1u_1 = m_2v_2 + m_3v_3$. Identify the statement that best describes the interaction between the two objects.

A The objects lose momentum during the collision.

B The objects collide and move apart after the collision.

C The objects collide and stick together upon collision.

D It is an explosion in which an object breaks apart.

4 The conservation of momentum in an interaction is given by the equation $m_1u_1 + m_2v_2 = m_3v_3$. Identify the statement that best describes the interaction between the two objects.

A The objects lose momentum during the collision.

B The objects collide and move apart after the collision.

C The objects collide and stick together upon collision.

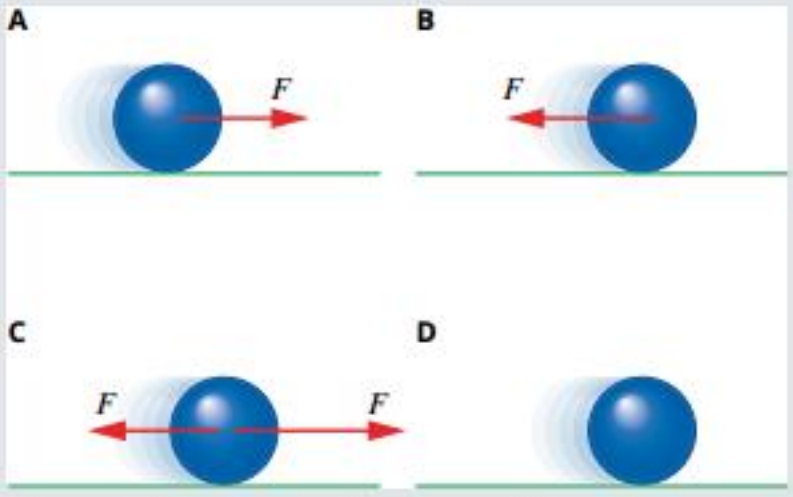
D It is an explosion in which an object breaks apart.

5 A car designer wants to reduce the force felt by the occupants of a car in the event of a crash. State whether they should try to reduce or increase the time it takes for the occupants to stop during the crash.

Apply

6 A ball experiences an applied force of 50 N to the right and a frictional force of 20 N to the left. Draw a free-body diagram of this scenario.

7 A bowling ball rolls along a smooth wooden floor at constant velocity, as shown in the diagram. Ignoring the effects of friction and air resistance, identify the diagram (A, B, C, or D) that correctly indicates the forces acting on the ball.



8 A child wearing a backpack jumps from a tree and lands on his feet on the ground. Select one or more correct statements about the factors that will affect the force on his knees and ankles when he lands.

A Wearing shoes with cushioned soles will reduce the force.

B Bending his knees as he lands will increase the force.

C Landing on harder ground will increase the force.

D Jumping from a lower branch will decrease the force.

The following information relates to questions ***9–12****.*

A student is travelling to school on a train. When the train starts to move, she notices that standing passengers lurch towards the back of the train before grabbing a handrail to stop themselves from falling.

9 Explain whether a force has acted on the passengers to push them backwards. Justify your answer.

10 The student holds onto a handrail to stop themselves falling. They apply a force of 80 N backwards to the handrail when the train moves. Determine the magnitude and direction of the reaction force.

11 The force the student applies on the handrail can be labelled as $F_{\text{on handrail by student}}$. Determine the label of the reaction force.

12 The student manages to find a seat and notices the force of the seat pushing up on them. They decide the force of the seat acting on them is the reaction force to their weight force. Determine whether the student is correct.

Analyse

*The following information relates to questions **13** and **14**.*

A tennis ball is thrown at a stationary bowling ball of mass 5.0 kg. The tennis ball rebounds and the bowling ball rolls forwards very slowly.

13 Identify the statement that best describes the forces that the two balls exert on each other during the collision.

A The forces are equal.
B The tennis ball exerts the greater force.
C The bowling ball exerts the greater force.
D The forces are equal in magnitude and opposite in direction.

14 Select the statement that best describes how the change in momentum of the tennis ball compares to the change in momentum of the bowling ball.

A They are equal.
B The tennis ball experiences a greater change of momentum.
C The bowling ball experiences a greater change of momentum.
D They are equal in magnitude and opposite in direction.

15 A box has forces of 14 N west, 45 N east and 20 N west acting on it. Calculate the net force acting on the box, and state what will happen as a result.

16 A rally car gets stuck in the mud, so three spectators try to help push it out. The mud exerts a frictional force of 700.0 N on the car. The spectators provide forces of 9800 N forwards, 14 000 N backwards and 7200 N forwards. Determine whether they push the car out of the mud.

17 Calculate the mass of an object if it accelerates at $9.20\,\text{m s}^{-2}$ east when a force of 352 N east acts on it.

18 Calculate the momentum of a 100.0 g frisbee travelling at $5.0\,\text{m s}^{-1}$ north.

19 Calculate the final velocity of a 14.0 kg remote-controlled car moving at $3.75\,\text{m s}^{-1}$ east, when a net force of 62.0 N west acts on it for 2.00 seconds.

20 Calculate the change in momentum of a 155 kg rock if its velocity changed from $6.50\,\text{m s}^{-1}$ east to $3.25\,\text{m s}^{-1}$ east in 8.50 s.

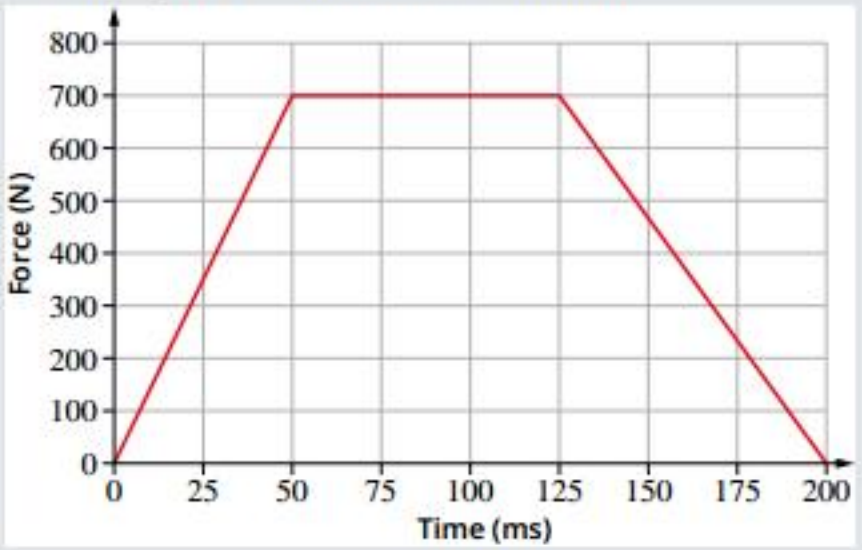
21 An egg hits the floor with a force of 0.50 N and its velocity changes to zero in 3.0 ms. Calculate the impulse of the egg.

22 An astronaut in a protective suit has a total mass of 154 kg and throws a 40.0 kg toolbox away from the space station. The astronaut and toolbox are initially stationary. After it has been thrown, the toolbox moves at $2.15\,\text{m s}^{-1}$. Calculate the velocity of the astronaut just after throwing the toolbox.

23 Nina throws a 50.0 g snowball at Katy, but it breaks into two equal pieces in mid-air. If the pieces move off with a velocity of $5.0\,\text{m s}^{-1}$, calculate the initial velocity of the snowball.

*The following information relates to questions **24–28**.*

The force versus time graph for a deflated ball being thrown against the wall can be seen below.



24 Determine the peak force experienced by the ball.

25 Determine how long the ball is in contact with the wall.

26 Calculate the impulse experienced by the ball.

27 Determine why the wall does not move even though the ball has applied a force to it.

28 A tennis ball of mass 57.5 g is tested for compliance with tennis regulations by being dropped from a height of 251 cm onto concrete. A bounce height of 146 cm is deemed acceptable. Calculate the magnitude of the force on the ball if it is in contact with the floor for 0.0550 s.

Interpret

29 Daku is playing baseball. He decides to tap the ball into play so that the ball is moving slowly into the infield. This is called a bunt play. Propose what Daku would have to do to adapt his swing to make this play.

30 In a tug of war, two teams of eight people hold a rope between them and try to pull the other team towards them. If you were in charge of one of two teams of identical mass in a tug of war contest, propose how you would maximise the chance of your team winning.

31 An astronaut in a small spacecraft decides he could move the spacecraft by pushing hard on one of its inside walls. Predict what would result from his action.

32 A student conducts an experiment with a basketball and a tennis ball. He drops each ball onto the ground and notes the height of their bounces. He then decides to drop the balls together with the tennis ball resting on top of the basketball as they fall. Predict what would happen. Justify your answer.

33 Newton's cradle is a popular toy in which a series of metal balls hang on strings next to each other. The end ball is pulled away from the rest and allowed to swing back towards the others. The collision causes one ball at the other end to swing away from the others. If two balls are pulled away and released, they will swing back and collide with others and cause two balls to swing away from the other end. Doing the same with three balls will cause three balls to swing away. Describe this action in terms of momentum.

Data analysis

DATA SET 1

The information below applies to Questions 1–4.
A student is investigating the following research question:

What is the relationship between impact time and force experienced during a collision?

They conducted the experiment with two different crumple zone designs. The data was collected and can be seen in Table 1 and Table 2. The data was processed into Figure 1.

TABLE 1: Results from the trial with the first crumple zone.

Time (s)	Force (N)
0.000	0
0.005	2.1
0.010	3.9
0.015	5.2
0.020	5.9
0.025	5.7
0.030	4.2
0.035	3.0
0.040	2.2
0.045	0

TABLE 2: Results from the trial with the second crumple zone.

Time (s)	Force (N)
0.000	0
0.005	1.8
0.010	3.4
0.015	3.8
0.020	4.1
0.025	4.2
0.030	4.0
0.035	3.8
0.040	2.6
0.045	1.6
0.50	0.8
0.55	0

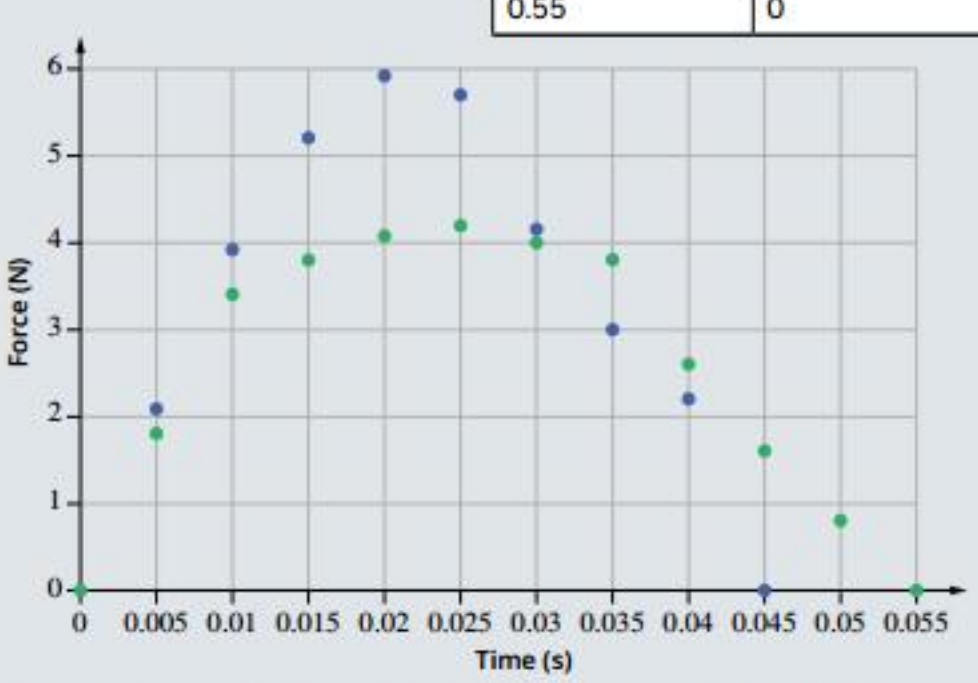


FIGURE 1 Collated force–time results from both crumple zone designs. The results for the first crumple zone are in blue and for the second crumple zone are in green.

Question 1 (2 marks)

Use the graph to identify which design experienced the greatest maximum force. Provide reasoning using the dataset.

Question 2 (2 marks)

Contrast the impact time and maximum force experienced by each of the crumple zone designs.

Question 3 (1 mark)

Determine the relationship between collision time and maximum force experienced during a collision.

Question 4 (2 marks)

Draw a conclusion about which design would be the better suited as a crumple zone to improve occupant safety during a collision.

welcome to

CHAPTER

08 Energy

This chapter explores how mechanical energy changes form and how such transformations relate to mechanical work. When a force acts through a distance, work is done. The rate of doing that work over a period of time is called *power*.

In Chapter 7 it was noted that, when objects collide, momentum is conserved. Similarly, in a collision, energy is conserved. Collisions in which kinetic energy is conserved are referred to as **elastic collisions**. In other collisions, some kinetic energy is transformed to other forms of energy (for example, sound and heat or—if the colliding object is permanently deformed—elastic potential energy). In these collisions, the *total* energy is conserved, but the kinetic energy is not. These types of collisions are referred to as **inelastic collisions**.

Syllabus subject matter

ENERGY

- Describe the concepts of mechanical work, kinetic energy and gravitational potential energy. **8.1, 8.2, 8.3**
- Solve problems involving work done by a force using $W = \Delta E$ and $W = Fs$. **8.1**
- Solve problems involving kinetic energy and gravitational potential energy using $E_k = \frac{1}{2}mv^2$ and $\Delta E_p = mg\Delta h$. **8.2, 8.3**
- Analyse the area under a force–displacement graph using geometric methods. **8.1**
- Interpret energy–time graphs. **8.3, 8.5**
- Discuss the differences between elastic and inelastic collisions. **8.4**
- Solve problems involving elastic collisions and inelastic collisions (including explosions) using $\Sigma\frac{1}{2}mv^2_{\text{before}} = \Sigma\frac{1}{2}mv^2_{\text{after}}$ **8.4**

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8.1 Work

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the concept of mechanical work and how work is done when energy changes form
- solve problems involving work done when energy is transferred or transformed using $W = \Delta E$
- solve problems involving work done when a force acts through a distance using $W = Fs$
- analyse force–displacement graphs and calculate the work done.

The words 'energy' and 'work' are commonly used to describe a variety of everyday situations. However, these words have specific definitions when used in a scientific context. They are two of the most important concepts in physics, allowing physicists to explain phenomena on a range of scales from collisions of subatomic particles to the interactions of galaxies.

DEFINING WORK

When a force acts on an object and causes energy to be transferred or transformed, then **work** is said to be done on the object. Force is a vector quantity; energy and work are both scalar quantities.

The SI unit for work and energy, the joule (J), is named after the English scientist James Prescott Joule. He was the first person to show that kinetic energy could be transformed into thermal (heat) energy. The energy represented by 1 J is approximately the equivalent to the energy needed to lift a 1 kg mass (for example, 1 L of water) through a height of 0.1 m. More commonly, scientists work in units of kilojoules (1 kJ = 1000 J) or even megajoules (1 MJ = 1 000 000 J).

CALCULATING WORK DONE

Mechanical work is equal to the energy transferred or transformed during a change in mechanical energy. This can be represented using the equation $W = \Delta E$.

More specifically, mechanical work is defined as the product of the force causing the energy change and the displacement of the object in the direction of the force during the energy change.

Because work corresponds to a change in energy, the SI unit of work is also the joule. The definition of work, $W = Fs$, allows us to find a value for a joule in terms of other SI units.

$$1\,\text{J} = 1\,\text{N} \times 1\,\text{m} = 1\,\text{Nm}$$

A joule is equal to a newton-metre; so, a force of 1 N acting over a distance of 1 m does 1 J of work.

The joule can be defined in terms of fundamental units by using the definition of a newton:

$$1\,\text{J} = 1\,\text{N} \times 1\,\text{m} = 1\,\text{kg m s}^{-2} \times 1\,\text{m} = 1\,\text{kg m}^2\,\text{s}^{-2}$$

As both force and displacement are vector quantities, work is a scalar quantity because it is the product of the two. So, like energy, work requires no direction to be fully defined.

$W = \Delta E$
where
W is work
ΔE is the change in energy.

$W = Fs$
where
W is work (J)
F is force (N)
s is the displacement in the direction of the force (m).

Worked example 8.1.1

CALCULATING WORK

The force exerted by the engine of a motorcycle acts in the same direction as the motorcycle's motion. Calculate the work done if the engine exerts a force of 3400 N for a distance of 80.0 m.

Thinking	Working
Recall the expression for work in terms of force and displacement.	$W = Fs$
Substitute in the data values.	$W = 3400 \times 80.0$
Complete the calculation and include correct units.	$W = 270000$ J

➤ Try yourself 8.1.1

CALCULATING WORK

A rope exerts a force of 53 N in the direction of motion of a barge on a river. The rope tows the barge 140 m. Calculate the work done on the barge.

FORCE AND DISPLACEMENT

A force–displacement graph illustrates the way a force changes with displacement. For a situation where the force is constant, this graph is simple. For example, in Figure 8.1.1, the force–displacement graph for a person picking up a box will be a flat horizontal line if the force applied to the box is constant throughout the lift.

As the box is lifted, work is done on the box and is transformed into **gravitational potential energy**. This gravitational potential energy would be transformed into kinetic energy if the box were dropped. The kinetic energy, in turn, would do mechanical work as the box hits the ground. Each time mechanical energy changes form, mechanical work is done.

If the person holds the box in the same position, they will use energy because of the way their muscles operate but no mechanical work is being done on the box. This is because the energy of the box is not changing ($\Delta E = 0$), and the box is not being displaced ($s = 0$). This illustrates the difference between the way the word 'work' is used in everyday life and the way it is used in mechanics.

Work can also be done when an elastic object, such as a spring, is stretched or compressed. The force–displacement graph for a spring being stretched is a straight line that passes through the origin and increases at a constant rate, as shown in Figure 8.1.2. The line shows the direct relationship between the amount the spring is stretched and the force that is applied. (Note: sometimes, you will see force–displacement graphs for elastic objects labelled as force–extension graphs. In this context, the term 'extension' is the same as 'displacement'.)

More commonly, a force will vary with the displacement, causing the force–displacement graphs to become more complex. For example, the force–displacement graph for a sports shoe in Figure 8.1.3 shows that the shoe is close to elastic—that is, the displacement is directly proportional to the force—for low displacements, but at high displacements the restoring force is more constant.

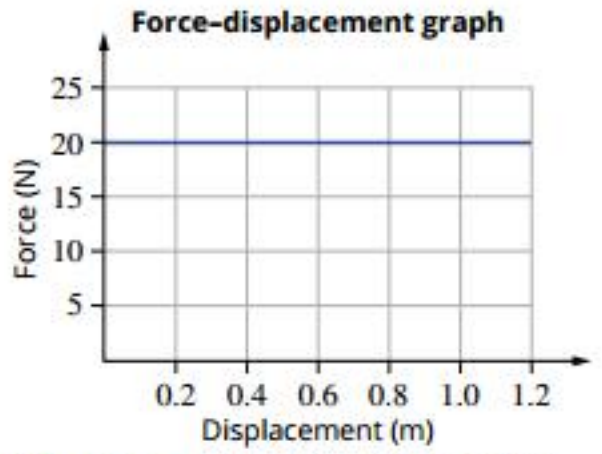


FIGURE 8.1.1 The force–displacement graph for a person picking up a box is a straight, horizontal line, when the force applied to the box by the man is constant throughout the lifting process.

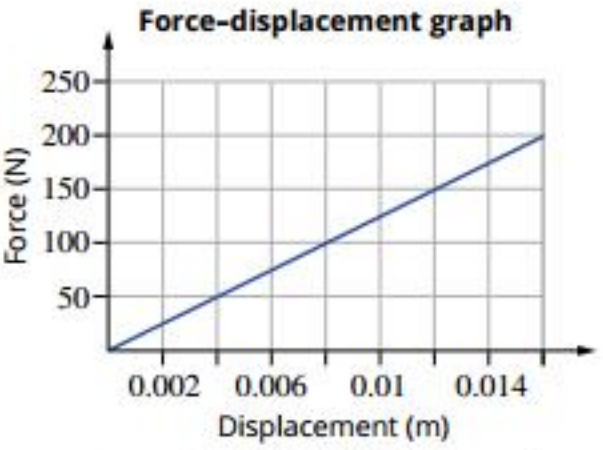


FIGURE 8.1.2 As a spring stretches, more force is required to keep stretching it. The force is proportional to the extension.

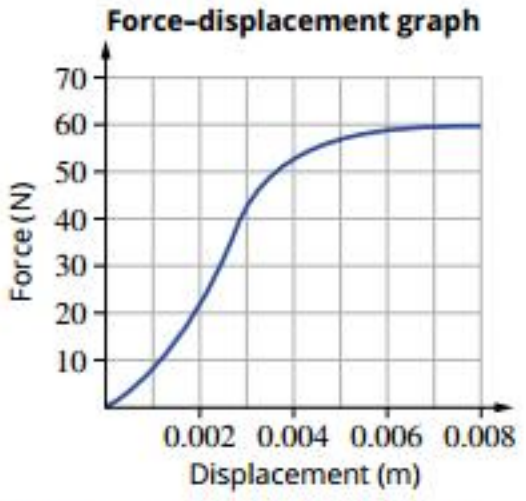


FIGURE 8.1.3 The force–displacement graph for a sports shoe is not a straight line; the change in force varies with how much the shoe has been stretched.

The amount of work done by a force can be calculated from the area under its force–displacement graph.

For a constant force, this is simple. Consider the earlier example of a person lifting a box (Figure 8.1.1). The area can be found by counting the number of 'force times distance' squares under the line.

Figure 8.1.4 has $6 \times 4 = 24$ squares.

Area of square: $5\,\text{N} \times 0.2\,\text{m} = 1\,\text{J}$

Each square has an area of 1 J so the total work done is 24 J.

Alternatively, this value could be found by calculating the total area under the force–displacement graph.

For Figure 8.1.4:

$$\begin{aligned} A &= l \times w \\ &= 20\,\text{N} \times 1.2\,\text{m} \\ &= 24\,\text{J} \end{aligned}$$

Note that this second method is the same as using the formula for work:

$$\begin{aligned} W &= Fs \\ &= 20 \times 1.2 \\ &= 24\,\text{J} \end{aligned}$$

The relationship works in this case because the force is constant.

Similar strategies can also be used when the force varies with the displacement. This will give an approximation if the graph is a curve. The work done in the force–displacement graph shown in Figure 8.1.5, for example, can be estimated by dividing the area into squares and counting the number of full and part squares or segments. The area of each segment equals the work done by a constant force during that small displacement and the total of all the segments will represent the total work done.

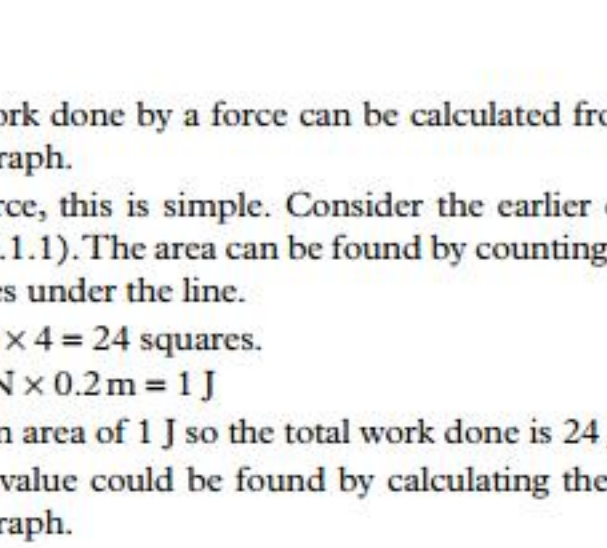


FIGURE 8.1.4 The area under a force–displacement graph gives the work done by the force.

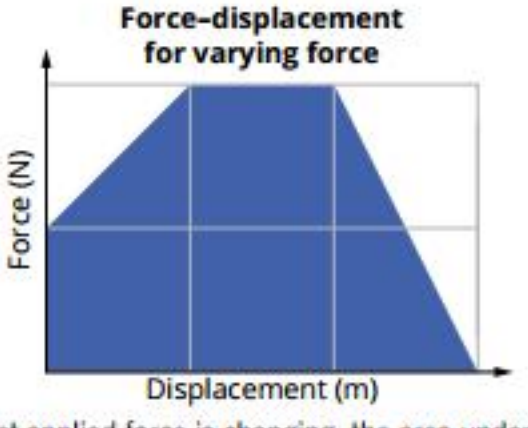
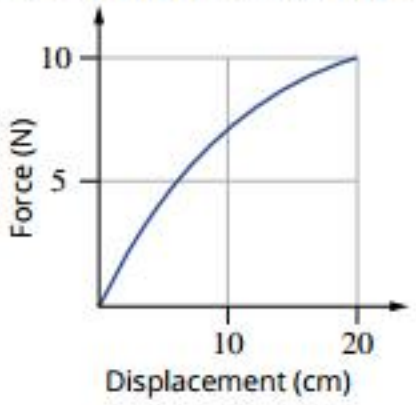


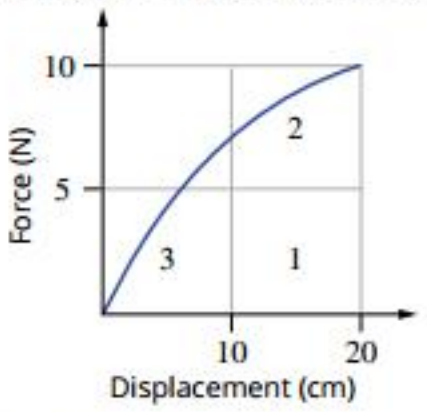
FIGURE 8.1.5 Where the net applied force is changing, the area under a force–displacement graph can be found by counting squares or by dividing the area into segments.

Worked example 8.1.2

WORK FROM THE AREA UNDER A FORCE–DISPLACEMENT GRAPH

Use the force–displacement graph for an elastic band to determine how much work is done in stretching the elastic band 20.0 cm. Give your answer to the nearest 0.50 J.

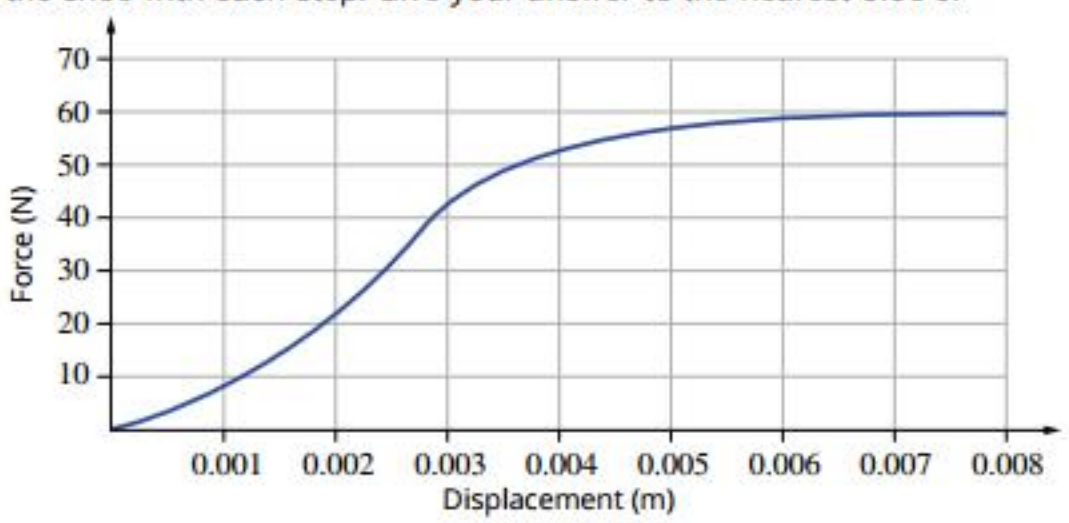


Thinking	Working
Determine the work value of each grid square or segment.	The dimensions of a grid square are: force: 5 N displacement: 10 cm = 0.1 m area of 1 square = 5 × 0.1 = 0.5 J
Count the number of grid squares under the curve. Only count grid squares that are more than half under the curve. If the curve cuts a square in half, count every second one.	Three of the squares shown below have more than half their area under the curve.  Number of squares = 3
Multiply the number of grid squares under the curve by the work value of each grid square.	$W = 3 \times 0.5\ \text{J} = 1.5\ \text{J}$ Approximately 1.5 J of work is done.

➤ Try yourself 8.1.2

WORK FROM THE AREA UNDER A FORCE–DISPLACEMENT GRAPH

The shoes of a jogger stretch by an average of 3 mm with each step. Use the force–displacement graph for a sports shoe to estimate how much work is done on the shoe with each step. Give your answer to the nearest 0.01 J.



8.1 Review

SUMMARY

- Mechanical work is done when mechanical energy is transformed, as represented by $W = \Delta E$.
- Work can be described as the transfer of energy to or from an object by the action of a force over a distance and is calculated using the formula $W = Fs$.
- The SI unit for work is the joule (J).
- Work can be done by lifting something to a higher position within a gravitational field. The object then has gravitational potential energy, allowing it to do work.
- The area under a force–displacement graph can be analysed to find the work done.
- Where the force is not constant so that the graph is a curve, the work done can be approximated by dividing the area under the graph into smaller segments and totaling those segments.

KEY QUESTIONS

Describe

1 State the formula that expresses work as a relationship between force and displacement.

2 Name the SI unit for both work and energy.

3 Which of the following are vector quantities: work, energy, force, displacement?

Apply

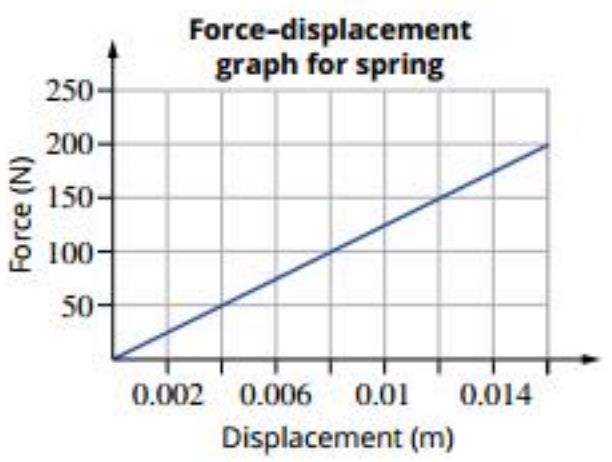
4 Explain why the equation $W = Fs$ cannot be used to calculate the work done in compressing a spring.

5 A ball is thrown straight up into the air and returns to be caught by the thrower. Describe the energy changes that occur during this process and the relationship to work done by gravity.

Analyse

6 When accelerating at the beginning of a ride, a cyclist applies a force of 500.0 N for a distance of 20.0 m. Calculate the work done by the cyclist on the bike.

7 A spring is stretched as shown in this force–displacement graph. Calculate the work done to stretch the spring by 0.016 m, using the formula for the area of a triangle.



8 A 1000 kg rocket is launched vertically upwards at a constant acceleration. When it reaches an altitude of 15 km, it is travelling at 900 m s^{-1}.

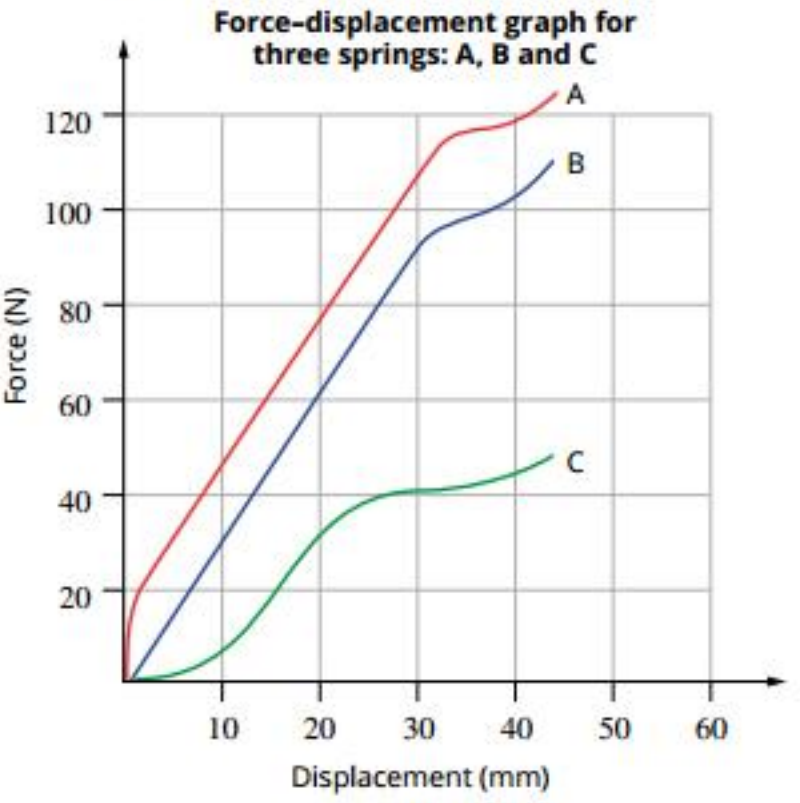
a Calculate the work done by the rocket.

b Using the work done by the rocket, determine the magnitude of its acceleration.

c Calculate the time taken for the rocket to reach 15 km in altitude.

9 A cyclist does 2700 J of work when she rides her bike at a constant speed for 150 m. Calculate the average force the cyclist applies over this distance.

10 Three different springs have the force–displacement graphs shown. Estimate the work done by stretching each of the springs by 40 mm.



8.2 Gravitational potential energy

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe forms of potential energy, including chemical, elastic, gravitational, magnetic, nuclear and spring
- calculate the gravitational potential energy change of an object using $\Delta E_p = mg\Delta h$
- calculate the work done on an object as a measure of its change in gravitational potential energy.

The potential energy of an object is associated with its position relative to another object or within a field. For example, an object suspended by a crane has gravitational potential energy because of its position in the Earth's gravitational field. In Chapter 4, you saw that electrical potential energy is stored by the separation of charges in a cell.

Some examples of potential energy are listed in Table 8.2.1.

TABLE 8.2.1 Types of potential energy and their causes

Type of potential energy	Cause
chemical	relative positions of atoms
elastic	attractive forces between atoms
gravitational	gravitational fields
magnetic	magnetic fields
nuclear	forces within the nucleus of an atom
spring	a stretched, compressed or wound spring

GRAVITATIONAL POTENTIAL ENERGY

Any object that is lifted above the Earth's surface has the capacity to cause change due to its position in the Earth's gravitational field. Gravitational potential, therefore, is a measure of the amount of energy available to an object due to its position in a gravitational field. The gravitational potential energy of an object can be calculated from the amount of work that must be done against gravity to get the object into its position.

Consider the weightlifter lifting a barbell in Figure 8.2.1. Assuming that the barbell is lifted at a constant speed, then the weightlifter must apply a lifting force equal to the force due to gravity on the barbell, F_g. The lifting force, F_l, is applied over a displacement, Δh, corresponding to the change in height of the barbell.

The work done against gravity by the weightlifter is:

$$W = F_{net}\, s = F_g \Delta h$$

The force due to gravity is given by the equation $F_g = mg$ so the work done can be written as:

$$W = mg\Delta h$$

The work carried out in this example has resulted in the transformation of chemical energy within the weightlifter into gravitational potential energy. Therefore, the change in gravitational potential energy of the barbell is:

$$\Delta E_p = mg\Delta h$$

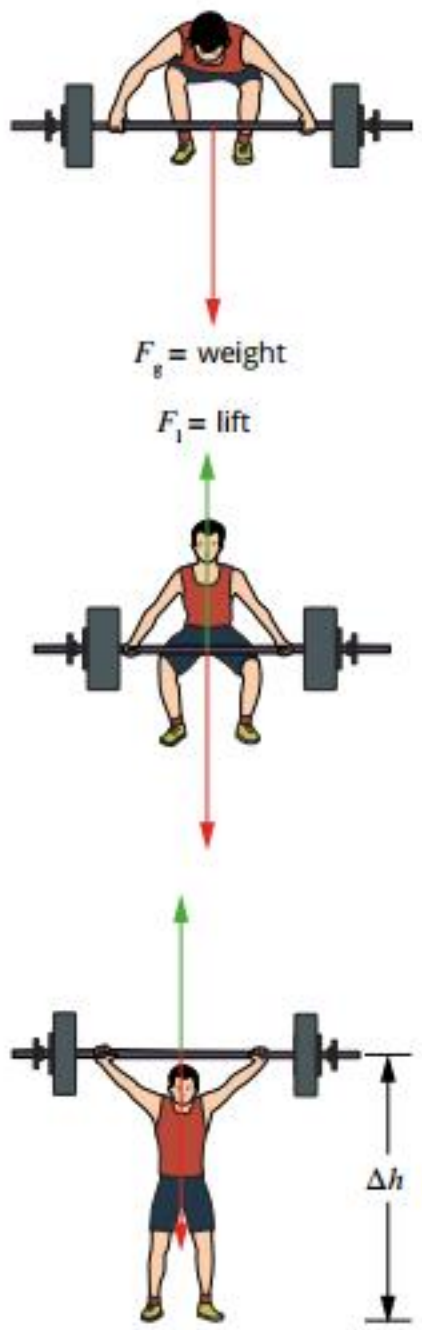


FIGURE 8.2.1 A weightlifter applies a constant force over a fixed distance to give the barbell gravitational potential energy.

The change in gravitational potential energy of an object, due to the work done against a gravitational field, is given by:

$\Delta E_p = mg\Delta h$

where

ΔE_p is the change in gravitational potential energy (J)

m is the mass of the object (kg)

g is the magnitude of the gravitational field strength (9.8 N kg^{-1} downwards on Earth)

Δh is the change in height of the object (m).

Units of *g*

Acceleration due to gravity can be expressed in units of N kg^{-1} or m s^{-2}. A newton is defined as a kg m s^{-2}, so:

$$\text{N kg}^{-1} = \frac{\text{N}}{\text{kg}} = \frac{\cancel{\text{kg}}\,\text{m s}^{-2}}{\cancel{\text{kg}}} = \text{m s}^{-2}$$

Use m s^{-2} when calculating acceleration due to gravity.

Use N kg^{-1} when measuring the force on a mass due to gravity.

Worked example 8.2.1

CALCULATING THE CHANGE IN GRAVITATIONAL POTENTIAL ENERGY

A weightlifter lifts a barbell that has a total mass of 80.0 kg from the floor to a height of 1.8 m above the ground. Calculate the change in gravitational potential energy of the barbell during this transformation.

Thinking	Working
Recall the formula for the change in gravitational potential energy.	$\Delta E_p = mg\Delta h$
Substitute the values for this situation into the equation.	$\Delta E_p = 80.0 \times 9.8 \times 1.8$
State the answer with appropriate units and significant figures.	$\Delta E_p = 1411.2$ J $= 1.4$ kJ

➤ Try yourself 8.2.1

CALCULATING THE CHANGE IN GRAVITATIONAL POTENTIAL ENERGY

A person doing their grocery shopping lifts a 5.0 kg grocery bag to a height of 30.0 cm. Calculate the change in gravitational potential energy of the grocery bag during this transformation.

CALCULATING GRAVITATIONAL POTENTIAL ENERGY AND THE 'REFERENCE LEVEL'

When calculating the change in gravitational potential energy, it is important to define the height that corresponds to zero potential energy ($E_p = 0$), known as the reference level. Often, this can be taken to be the ground or sea level, but the appropriate reference level is not always obvious.

It does not matter which point is taken as the zero potential energy reference level, as long as the chosen point is used consistently throughout a particular problem (Figure 8.2.2). If objects move below the initial reference level, then the change in potential energy will be negative.

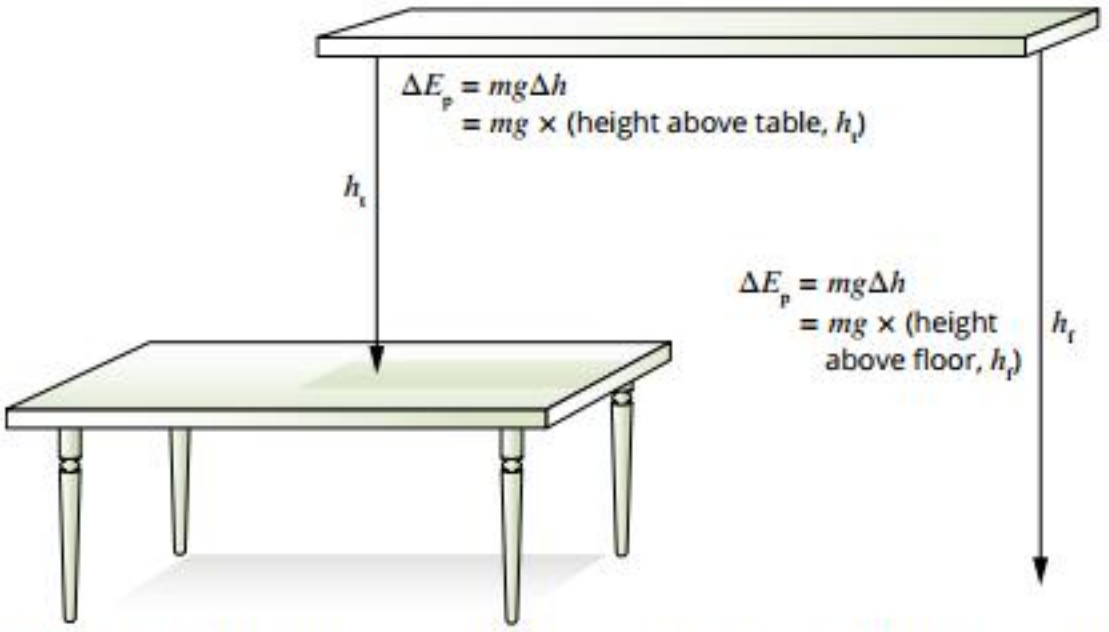


FIGURE 8.2.2 In this situation, the zero potential energy reference point could be taken as either the level of the table or the floor.

Worked example 8.2.2

CALCULATING THE CHANGE IN GRAVITATIONAL POTENTIAL ENERGY RELATIVE TO A REFERENCE LEVEL

A weightlifter (m = 60.0 kg) lifts a 50.0 kg bar through a distance of 45 cm. Calculate the increase in gravitational potential energy of the bar with each lift she makes. Use $g = 9.8\,\text{N kg}^{-1}$.

Thinking	Working
Recall the formula for the change in gravitational potential energy.	$\Delta E_p = mg\Delta h$
Identify the relevant values for this situation. Only the mass of the bar is being lifted (the weightlifter's mass is a distractor). Take the weightlifter's body as the zero potential energy level.	$m = 50.0\,\text{kg}$ $g = 9.8\,\text{N kg}^{-1}$ $\Delta h = 45\,\text{cm} = 0.45\,\text{m}$
Substitute the values for this situation into the equation.	$\Delta E_p = 50.0 \times 9.8 \times 0.45$
State the answer with appropriate units and significant figures.	$\Delta E_p = 220\,\text{J}$

➤ Try yourself 8.2.2

CALCULATING THE CHANGE IN GRAVITATIONAL POTENTIAL ENERGY RELATIVE TO A REFERENCE LEVEL

A father picks up his baby from its bed. The baby has a mass of 6.0 kg and the mattress of the bed is 70.0 cm above the ground. When the father holds the baby in his arms, it is 125 cm off the ground. Calculate the increase in gravitational potential energy of the baby, using g as $9.8\,\text{N kg}^{-1}$.

8.2 Review

SUMMARY

- The potential energy of an object refers to its position relative to another object or within a field.
- Forms of potential energy include chemical, elastic, gravitational, magnetic, nuclear and spring.
- Gravitational potential is a measure of the amount of energy available to an object due to its position in a gravitational field.
- The force due to gravity is equal to $F_g = mg$.
- The change in gravitational potential energy of an object (ΔE_p) due to the work done against a gravitational field is given by $\Delta E_p = mg\Delta h$.

KEY QUESTIONS

Describe

1 State the equation used to calculate the difference in gravitational potential energy of a mass at two points, when one point is h m higher than the other.

2 What is the SI unit of measurement for gravitational potential energy?

Apply

3 Explain why you can choose any height you like as the 'zero' reference level of gravitational potential energy.

4 If air resistance and other forms of frictional force are ignored, moving something horizontally in a gravitational field does not result in work being done on the object by gravity. Explain why this is the case.

Analyse

5 Calculate the gravitational potential energy of a 115 kg climber standing at the top of Mount Kosciuszko when they are at an altitude of 2228 m above sea level.

6 An athletics coach is stacking shot-puts onto a shelf 1.0 m off the ground after training. Each shot-put has a mass of 500 g and all are being lifted from ground level. The coach stacks 15 shot-puts.

a Calculate the amount of work done in lifting all the shot-puts.

b Determine the total gravitational potential energy of all the shot-puts once they are lifted on to the shelf.

c One of the shot-puts rolls off the shelf just after the coach has finished. Calculate the gravitational potential energy of this one shot-put when it is halfway back to the ground.

7 When climbing Mount Everest ($h = 8848$ m), a mountain climber stops to rest at North Base Camp ($h = 5150$ m). If the mountain climber has a mass of 65.0 kg, calculate the gravitational potential energy she will gain in the final section of the climb (from base camp to the summit). For simplicity, assume that g remains at 9.8 N kg^{-2}.

8 An 80.0 kg skydiver falls from 20000.0 m to 10000.0 m.

a Calculate the work done on the skydiver by gravity (ignore air resistance and assume that g remains at 9.8 N kg^{-1}).

b Calculate the change in gravitational potential energy of the skydiver.

c Compare your answers for parts **a** and **b**.

8.3 Kinetic energy

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the concept of kinetic energy
- calculate the kinetic energy of an object using $E_k = \frac{1}{2}mv^2$
- calculate changes in the kinetic energy of an object
- interpret energy–time graphs.

Kinetic energy is the energy associated with motion. Any moving object has kinetic energy.

In some types of kinetic energy, the moving objects are not easily visible. An example of this is thermal energy, which is a type of kinetic energy related to the movement of particles. Table 8.3.1 lists and describes some different types of kinetic energy.

TABLE 8.3.1 Types of kinetic energy and their associated moving objects

Type of kinetic energy	Type of motion
rotational kinetic	rotating objects
sound	air molecules vibrating
thermal	movement of atoms, ions or molecules due to temperature
translational kinetic	objects moving in a straight line

CALCULATING KINETIC ENERGY

The kinetic energy, E_k, of an object of mass m and velocity v is given by:

$$E_k = \frac{1}{2}mv^2$$

Like other forms of energy, kinetic energy is measured in joules (J).

Consider the dynamics cart in Figure 8.3.1 of mass, m, starting at rest ($u = 0$). It is pushed with force, F, which acts while the cart undergoes a displacement, s, and gains a final velocity, v.

The force does work on the cart equal to $W = Fs$. This work done changes the kinetic energy of the cart.

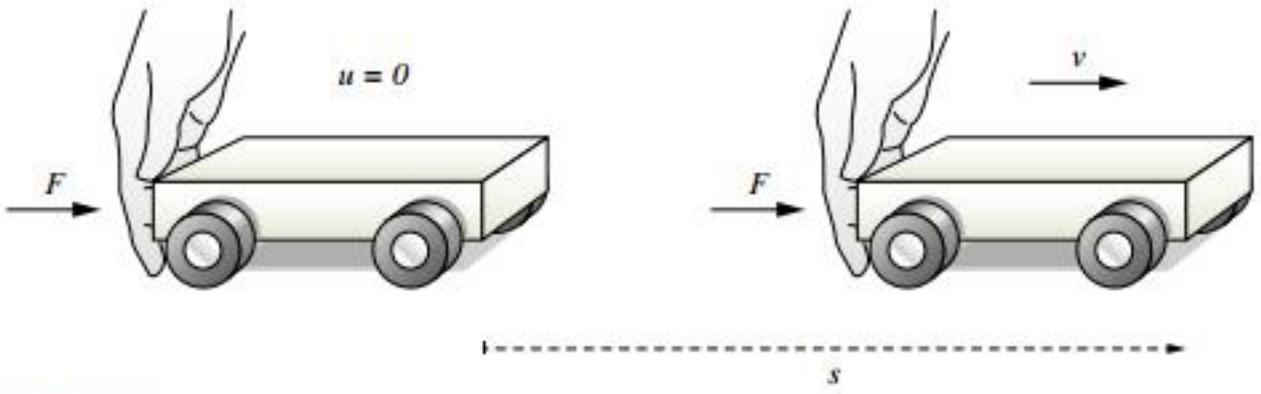


FIGURE 8.3.1 The kinetic energy of a dynamics cart can be calculated by considering the work done on the cart by a force (F) acting on it over a given displacement (s).

The relationship between the work done and the change in kinetic energy is $W = \Delta E$. As the cart changes velocity from u to v, this becomes:

$$W = \Delta E_k$$
$$= \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

$E_k = \frac{1}{2}mv^2$

where

E_k is kinetic energy (J)

m is mass (kg)

v is velocity ($m\,s^{-1}$).

This equation is known as the **'work–energy theorem'** because it shows the theoretical relationship between work and energy.

As $u = 0$, and assuming that no energy is lost as heat or noise and that all the work is converted into kinetic energy, this simplifies to the mathematical definition for the kinetic energy, E_k, of the cart in terms of its mass and velocity:

$$E_k = \frac{1}{2}mv^2$$

Worked example 8.3.1

CALCULATING KINETIC ENERGY

A car with a mass of 1200 kg is travelling at 90.0 $km\,h^{-1}$. Calculate its kinetic energy at this speed.

Thinking	Working
Convert the car's speed to m s^{-1}.	$90.0\ km h^{-1} = \frac{90.0}{1} = \frac{90000}{3600} = 25\ m s^{-1}$
Recall the equation for kinetic energy.	$E_k = \frac{1}{2}mv^2$
Substitute the values for this situation into the equation.	$E_k = \frac{1}{2} \times 1200 \times 25^2$
State the answer with appropriate units.	$E_k = 375000$ J $= 380$ kJ

➤ Try yourself 8.3.1

CALCULATING KINETIC ENERGY

A person crossing the street is walking at 5.0 $km\,h^{-1}$. If the person has a mass of 80.0 kg, calculate their kinetic energy.

Kinetic energy and energy–time graphs

Plotting a graph that shows kinetic energy against time can be a useful tool in understanding the motion of an object.

Consider the dynamics cart from Figure 8.3.1. When the cart is at rest, the kinetic energy of the cart would be zero. When a force is applied, however, the velocity of the cart increases and, hence, the cart's kinetic energy will also increase. Once the applied force is removed, the cart's velocity and kinetic energy remain constant (assuming no force of friction or drag) as no further work is done on the cart ($\Delta E_k = 0$). This is illustrated in Figure 8.3.2.

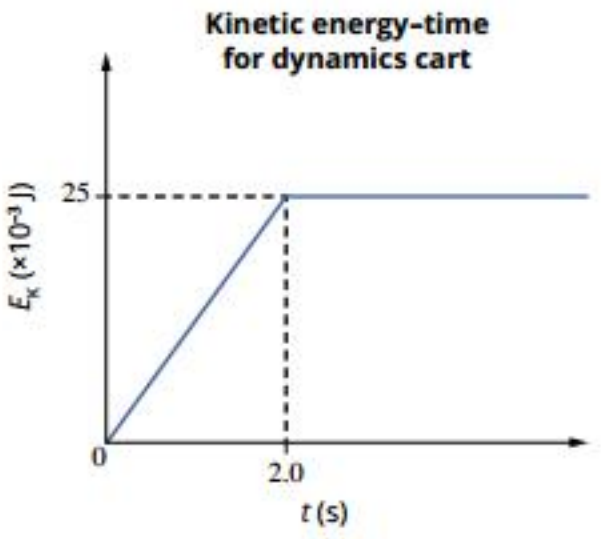


FIGURE 8.3.2 Graph illustrating the increase in kinetic energy as a force is applied to a dynamics cart for 2.0 seconds. Once the force is removed, on a frictionless source with no other horizontal forces present, the kinetic energy will remain constant.

The velocity of the cart at any given time can be obtained from the graph. For example, at $t = 1.0$ s, the kinetic energy of the cart is equal to 12.5×10^{-3} J. This value and the mass of the cart can then be substituted into $E_k = \frac{1}{2}mv^2$ and rearranged to find the velocity.

The work done by the force can also be determined by interpreting the graph. The graph shows that the force has been applied for 2.0 seconds, causing the kinetic energy of the cart to increase from zero to 25×10^{-3} J. The initial gradient of the graph (up to 2.0 s) indicates that the work done by the force is constant. The zero gradient of the graph (after 2.0 s) indicates that there is no longer an external force acting in the direction of the motion. Because no further work is done, kinetic energy remains constant.

Worked example 8.3.2

INTERPRETING ENERGY–TIME GRAPHS

A cart with a mass of 200 g is acted on by an external horizontal force for 2.0 seconds. The graph of the cart's kinetic energy against time is shown in Figure 8.3.2. Interpret this graph to answer the following questions.

a Describe the motion of the cart.

Thinking	Working
The graph of kinetic energy against time has a straight line diagonally upwards between $t = 0$ and $t = 2.0$ s. The line is then horizontal from $t = 2.0$ s onwards.	The kinetic energy of the cart increases at a constant rate between $t = 0$ and $t = 2.0$ s. As $E_k = \frac{1}{2}mv^2$ and the mass is constant, v must also be increasing; that is, the cart is accelerating. From $F = ma$, an unbalanced net force must be acting. From $t = 2.0$ s, the kinetic energy is constant. Therefore, the velocity must also be constant, and no force is acting.

b Calculate the speed of the cart once the force has stopped acting.

Thinking	Working
Recall the equation for kinetic energy.	$E_k = \frac{1}{2}mv^2$
When the force has stopped acting, the kinetic energy is constant. From the graph, this is at $E_k = 25 \times 10^{-3}$ J. Substitute the values for this situation into the equation and simplify.	$25 \times 10^{-3} = \frac{1}{2} \times 0.200 \times v^2$ $= 0.100 \times v^2$
Rearrange to make velocity the subject.	$v = \sqrt{\frac{25 \times 10^{-3}}{0.100}}$
State the answer with appropriate units. Note speed is a scalar quantity and does not require a direction.	$v = 0.50\ \text{m s}^{-1}$

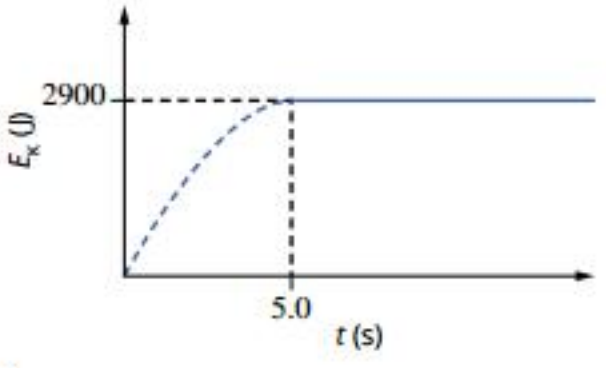
c Determine the work done on the cart by the force.

Thinking	Working
Recall that $W = \Delta E$	From the graph, this is the change in kinetic energy, E_k, between $t = 0$ and $t = 2.0$ s. Work done $= 25 \times 10^{-3}$ J $- 0$ J $= 25 \times 10^{-3}$ J

➤ Try yourself 8.3.2

INTERPRETING ENERGY–TIME GRAPHS

A skateboarder pushes off on the ground with one foot. The horizontal component of the force accelerates the board, causing the board and skater combined to gain a kinetic energy of 2900 J after 5.0 seconds. This is shown in the graph below. Interpret this graph to answer the following questions.



a Describe the motion of the skateboarder.

b Calculate the velocity of the skateboard and rider after 5 seconds if the combined mass of board and rider is 58 kilograms.

c Determine the work done on the ground by the skateboarder.

8.3 Review

SUMMARY

- Kinetic energy is the energy a body has resulting from the movement of an object.
- Types of kinetic energy include translational, rotational, thermal and sound energy.
- The kinetic energy, E_k, of an object of mass m (kg) with a velocity of v ($m s^{-1}$) is given by $E_k = \frac{1}{2} mv^2$. where E_k is the kinetic energy of the object in joules (J).
- The change in the kinetic energy of an object is given by $\Delta E_k = \frac{1}{2} mv^2 - \frac{1}{2} mu^2$, which is equal to the work done on the object.
- A graph of kinetic energy against time can be interpreted to learn about the motion of an object over time.

KEY QUESTIONS

Describe

1 State the name given to the form of mechanical energy that a mass has when it is in motion.

2 State the relationship between the kinetic energy and velocity of an object.

Apply

3 Identify the amount by which kinetic energy is increased when the mass of an object is doubled.

4 Identify the amount by which kinetic energy is increased when the velocity of an object is doubled.

Analyse

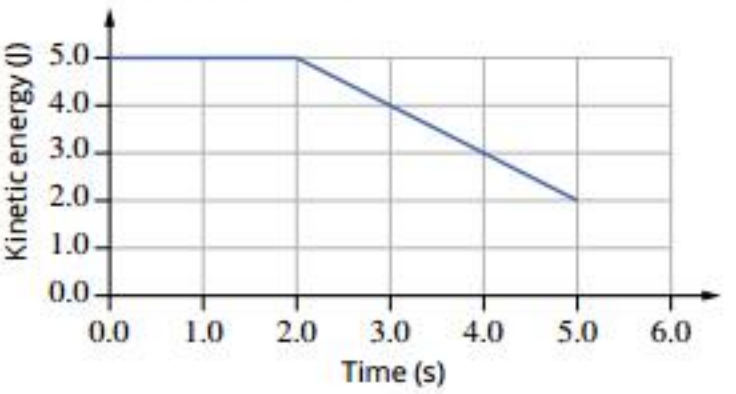
5 The mass of a motorbike together with its rider is 230 kg. If the motorbike is travelling at 80.0 $km h^{-1}$, calculate its kinetic energy.

6 A 1500 kg car is travelling at 17 $m s^{-1}$. Determine how much work its engine would need to do to accelerate the car to 28 $m s^{-1}$.

7 A cyclist has a mass of 72 kg and is riding a bicycle that has a mass of 9.0 kg. When riding at top speed, the combined kinetic energy of the cyclist and bicycle is 5.0 kJ. Calculate the top speed of the cyclist.

8 A school zone with a 40.0 $km h^{-1}$ speed limit lies within an area that has a 60.0 $km h^{-1}$ speed limit. Calculate the kinetic energy of a 2000.0 kg car at 40.0 $km h^{-1}$ and 60.0 $km h^{-1}$ and contrast the two answers.

9 A metal weight of mass 200 g is sliding across a horizontal surface as shown in the energy–displacement graph below. Part of the surface is frictionless, part is rough.



a Identify the section of the surface that is rough. Justify your answer.

b Determine the speed of the cube during the first 2.0 s

c Identify the amount of kinetic energy lost by the cube between $t = 2.0$ s and $t = 5.0$ s.

d What could have happened to the kinetic energy lost by the cube?

8.4 Conservation of energy

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state that energy is conserved – it is not created or destroyed
- solve problems involving energy transformations such as gravitational potential energy being transformed into kinetic energy
- calculate the mechanical energy of an object from its kinetic and potential energy
- contrast elastic and inelastic collisions
- solve problems involving elastic and inelastic collisions.

Recall that energy comes in many forms such as heat, light, sound, chemical energy and electrical energy. It is a scalar quantity and is measured in joules (J). Energy is also associated with the motion and position of an object; this is the mechanical energy of the object. In the motion problems of this chapter, moving objects have been described as having kinetic energy. An object can also have stored or gravitational potential energy because of its position relative to another object or within a field.

The transformation of gravitational potential energy to kinetic energy as an object increases velocity as it falls from a height is an illustration of the **law of conservation of energy**, a fundamental principle of nature. The law of conservation of energy states that energy is not created or destroyed, but can only **transform** from one form to another.

Sometimes, energy is transformed into forms that are not useful. For example, the friction of tyres on a road can cause them to heat up and reduce the kinetic energy of the car. The mechanical energy – that is, the kinetic and potential energy – has decreased as some energy has transformed into heat, but no energy has been lost. Mechanical energy is only conserved under ideal conditions, but in many cases it is a useful approximation.

ENERGY CONVERSIONS AND CONSERVATION OF ENERGY

To understand how energy is transformed, it is useful to analyse an example. Consider the example of the diver in Figure 8.4.1.

When the diver is at the greatest height of their motion, their gravitational potential energy will be at a maximum. As the diver falls, their gravitational potential energy decreases and their kinetic energy (and velocity) increases. A small amount of their kinetic energy will be transformed into heat and sound due to air resistance. By the time the diver reaches the pool surface, all the initial gravitational potential energy will have been transformed into other forms, mostly kinetic energy. The diver's total energy at this point will be almost exactly equal to the potential energy at the top; therefore, energy has been conserved.

The sum of the gravitational potential energy and the kinetic energy at any point during the dive is called the total mechanical energy and remains constant. This can be expressed as:

$$\text{total energy} = E_k + E_p$$

The same principle applies to any situation involving energy transfers or transformations in an isolated system.

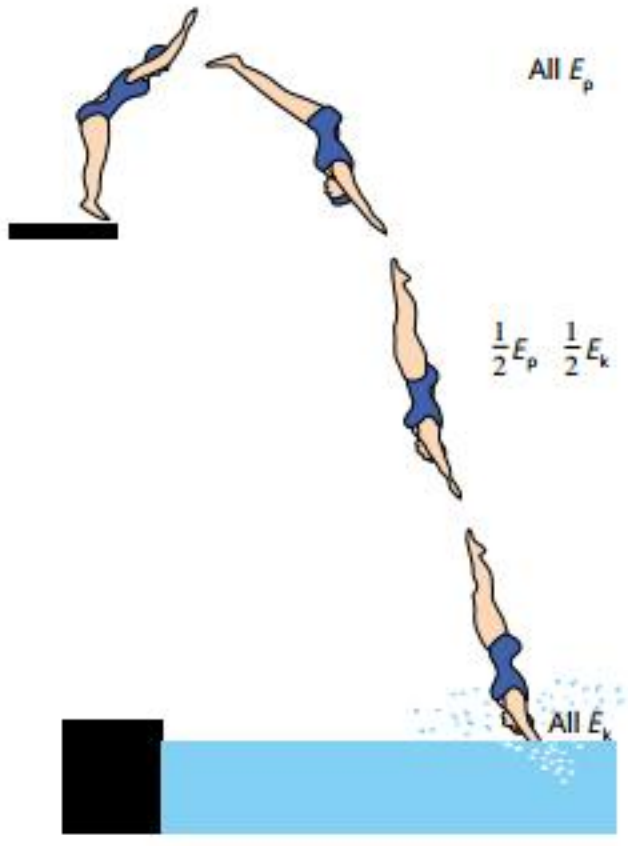


FIGURE 8.4.1 A diver loses gravitational potential energy but gains kinetic energy during the fall from diving board to water.

In an isolated system, the total energy is always conserved. Energy can be transformed from one kind to another, but the total amount stays the same.

Energy conversions

There are many situations where energy is transformed between kinetic and gravitational potential energy. For example, when a tennis ball bounces, as shown in Figure 8.4.2, much of its kinetic energy is transformed into gravitational potential energy as it rises, and then transforms back into kinetic energy as it falls.

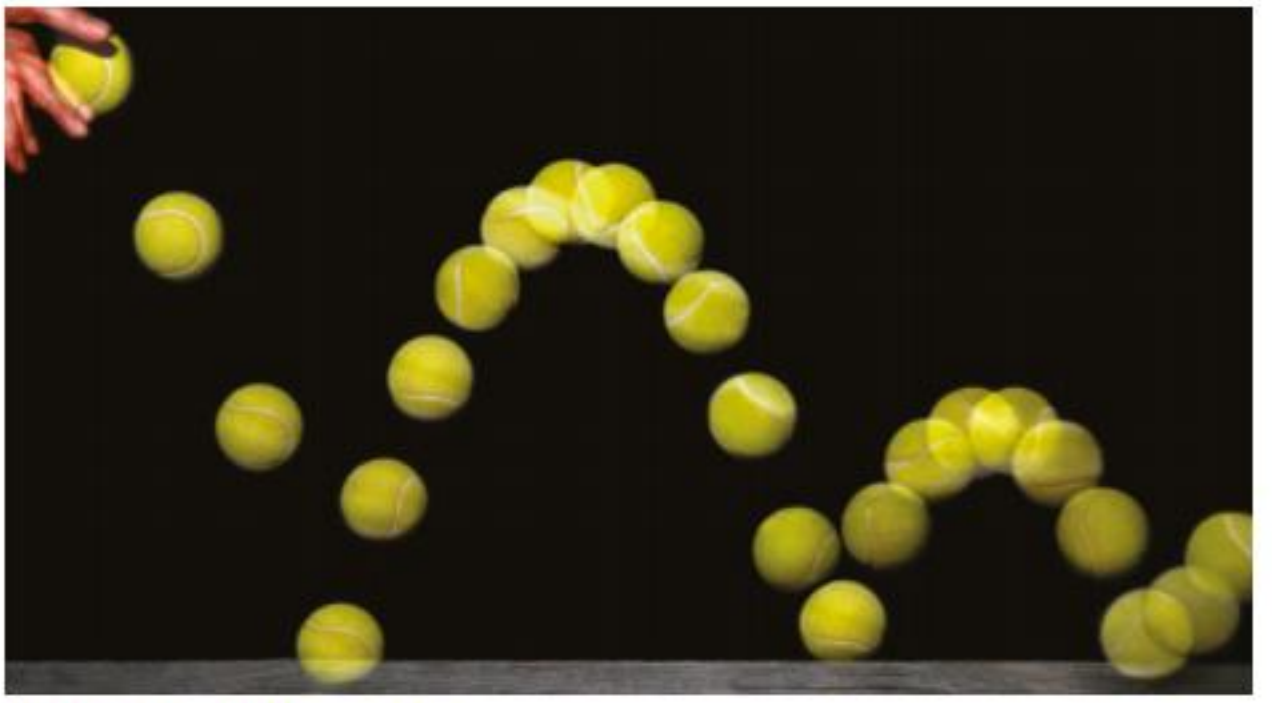


FIGURE 8.4.2 A bouncing tennis ball

Assume the tennis ball shown in Figure 8.4.3 has a mass of 60.0 g and is dropped from a height of 1.00 m. Initially, its total mechanical energy would comprise the sum of the kinetic energy, which would be 0 J, and the gravitational potential energy that is stored at this height ($g = 9.8\,\text{m s}^{-2}$):

$$\begin{aligned}\Delta E_p &= mg\Delta h \\ &= 0.0600 \times 9.8 \times 1.00 \\ &= 0.588\ \text{J}\end{aligned}$$

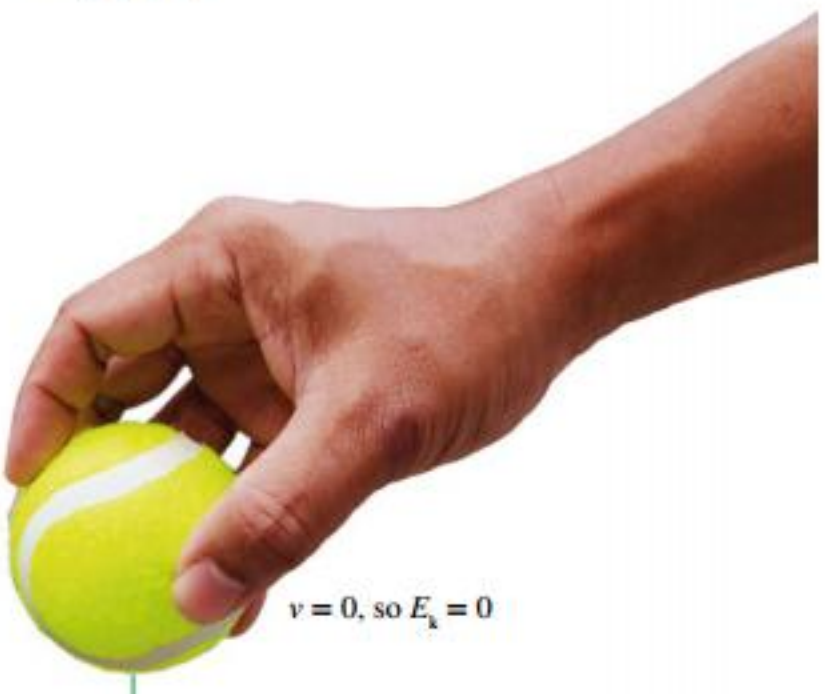


FIGURE 8.4.3 A falling tennis ball provides an example of conservation of mechanical energy.

At the instant the ball hits the ground, the total mechanical energy would comprise of the gravitational potential energy available to it and the kinetic energy just prior to hitting the ground. The gravitational potential energy is 0 J because the ball is at ground level. To determine the kinetic energy, the ball's velocity just before it hits the ground can be calculated using one of the equations of motion:

$$v^2 = u^2 + 2as.$$

When the ball is just about to hit the ground, the velocity can be calculated as follows:

$s = -1.00\,\text{m}$, $a = -9.8\,\text{m s}^{-2}$ and $u = 0\,\text{m s}^{-1}$:

$$v^2 = u^2 + 2as$$

$$v^2 = 0^2 + 2(-9.8 \times -1.00)$$

$$v = \sqrt{19.6}$$

$$= 4.43\,\text{m s}^{-1} \text{ downwards}$$

Therefore, the kinetic energy of the tennis ball just before it hits the ground is:

$$E_k = \frac{1}{2}mv^2$$

$$= \frac{1}{2} \times 0.06 \times 4.43^2$$

$$= 0.588\,\text{J}$$

Note that, at both the top and the bottom of the 1.00 m fall, the mechanical energy is the same.

At the top:

$$\text{total energy} = E_k + \Delta E_p$$

$$= \frac{1}{2}mv^2 + mg\Delta h$$

$$= 0 + 0.588$$

$$= 0.588\,\text{J}$$

At the bottom:

$$\text{total energy} = E_k + \Delta E_p$$

$$= \frac{1}{2}mv^2 + mg\Delta h$$

$$= 0.588 + 0$$

$$= 0.588\,\text{J}$$

The total mechanical energy remains constant throughout the drop. At the halfway point, $h = 0.500\,\text{m}$ and $v = 3.13\,\text{m s}^{-1}$:

$$\text{total energy} = E_k + \Delta E_p$$

$$= \frac{1}{2}mv^2 + mg\Delta h$$

$$= \left(\frac{1}{2} \times 0.0600 \times 3.13^2\right) + (0.0600 \times 9.8 \times 0.500)$$

$$= 0.294 + 0.294$$

$$= 0.588\,\text{J}$$

At this halfway point, the mechanical energy is evenly split between kinetic energy (0.294 J) and gravitational potential energy (0.294 J). Throughout the drop, the mechanical energy has been conserved.

Worked example 8.4.1

CALCULATING MECHANICAL ENERGY

Calculate the total mechanical energy of a 0.025 kg projectile that is at a height of 22 m and falling at 18 m s^{-1}.	
Thinking	**Working**
Recall the definition of mechanical energy and the principle of conservation of energy.	Mechanical energy is an object's kinetic energy plus its gravitational potential energy. The mechanical energy of a system remains constant. total energy = $E_k + \Delta E_p$ $= \frac{1}{2}mv^2 + mg\Delta h$
Substitute in the values for each variable.	$E_t = \left(\frac{1}{2} \times 0.025 \times 18^2\right) + (0.025 \times 9.8 \times 22)$
State the answer with appropriate units.	$E_t = 4.05 + 5.39$ $= 9.4$ J

➤ Try yourself 8.4.1

CALCULATING MECHANICAL ENERGY

A 3.2 kg object is moving upwards at 15.7 m s^{-1}. It is 22.2 m above the ground. Calculate its total mechanical energy.

Mechanical energy and energy–time graphs

A more complex example of energy conversions is provided by Figure 8.4.4, which shows the movement of a gymnast as they carry out a routine on a trampoline. Kinetic and gravitational potential energy changes are shown on the energy–time graph in Figure 8.4.4. Despite the complexity of the motion, the total energy of the gymnast remains the same during each airborne phase, as illustrated by the shaded parts of the graph. In these phases, the gymnast can be considered an isolated system.

However, upon landing on the bed of the trampoline, the gymnast's mechanical energy is transferred to elastic potential energy within the trampoline and so the total mechanical energy for the gymnast falls. Some of this energy is permanently transferred to the trampoline and its surrounds, lowering the total still available to the gymnast. The total energy of the gymnast, shown by the horizontal lines on the graph, decreases after each bounce.

Real-world energy transformations are never perfect, and some energy is always transferred to the surrounding system. For a system to continue operating (doing work), it must be provided with energy constantly. For example, the flexing of the gymnast's legs on take-off would add energy to the system, maintaining the mechanical energy or even increasing it until the gymnast's internal energy is exhausted.

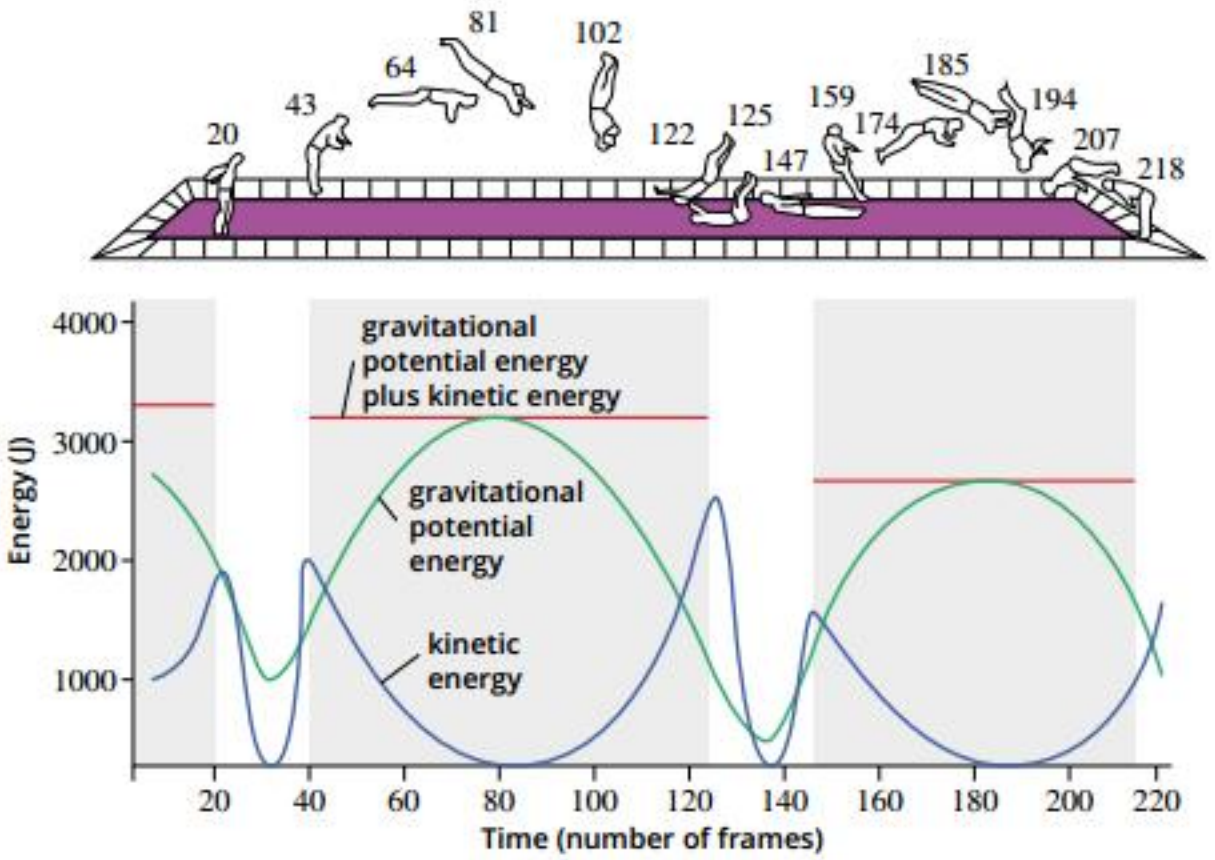


FIGURE 8.4.4 During each airborne stage of a gymnast's trampoline routine (shown by shading on the energy–time graph), mechanical energy is conserved, shown by the red horizontal lines on the graph. The graph shows the relationship between total energy, gravitational potential energy and kinetic energy. The numbers next to the gymnast correspond to the number of frames on the graph.

ELASTIC AND INELASTIC COLLISIONS

In a collision, two or more objects hit each other and exchange energy. For example, collisions occur between sports players (Figure 8.4.5) or between a bat and a ball, and more serious collisions occur in car crashes.

While total energy is always conserved, it can be transformed into different types of energy. Recall that an elastic collision is one in which the initial kinetic energy of all the objects involved is the same as the final kinetic energy. An inelastic collision is one in which the final kinetic energy is lower (not conserved). In an inelastic collision, energy is transformed into heat, sound and other forms of energy that cannot do mechanical work on the objects involved. Energy is also stored as elastic potential energy in the permanent deformation of the objects. The types of collisions are compared in Table 8.4.1.

FIGURE 8.4.5 Collisions often occur in sport.

TABLE 8.4.1 A comparison of the properties of elastic and inelastic collisions

	Elastic collision	Perfectly elastic collision	Inelastic collision	Perfectly inelastic collision
Momentum	conserved	conserved	not conserved	not conserved
Energy	approximately conserved	conserved	not conserved	not conserved
Energy losses	negligible energy is lost to heat, sound, deformation, and so on.	no energy losses	energy is lost to heat, sound, deformation, and so on.	energy is lost to heat, sound, deformation, and so on.
Result of collision	objects bounce apart	objects bounce apart	objects bounce apart	objects remain combined
Example	Newton's cradle	atomic particles	bouncing ball	arrow impacting a target

Recall that kinetic energy (E_k) is the energy of motion of a body, calculated using:

$$E_k = \frac{1}{2}mv^2$$

In a perfectly elastic collision, kinetic energy is transferred between objects, and no energy is transformed into heat, sound or stored elastic potential energy. In such cases, the relationship is stated as:

$$E_{k(before)} = E_{k(after)}$$

$$\Sigma\frac{1}{2}mv_{before}^{\ 2} = \Sigma\frac{1}{2}mv_{after}^{\ 2}$$

Perfectly elastic collisions do not exist in everyday situations, but they do exist in the interactions between atoms and subatomic particles. A collision between two billiard balls or the spheres in a Newton's cradle is almost perfectly elastic because very little of their kinetic energy is transformed into heat and sound energy, and there is little permanent deformation of the objects involved.

Collisions such as a bouncing basketball, a gymnast on a trampoline or a tennis ball being hit are moderately elastic, with about half the kinetic energy of the system being retained and little permanent deformation of the objects involved. The remaining half is transformed mostly into heat and sound energy.

Perfectly inelastic collisions are those in which the colliding bodies stick together after impact with no remaining kinetic energy. Some car crashes, a collision between a meteorite and the Moon, and a collision involving two balls of plasticine, are all examples of perfectly inelastic collisions. In these collisions, most or all of the initial kinetic energy of the system is transformed into other forms of energy. These collisions are sometimes referred to as 'sticky' collisions.

Worked example 8.4.2

CALCULATING ELASTIC COLLISIONS

A 35 kg child is sliding at 4.0 m s^{-1} on ice skates on a frozen pond and collides elastically with her large stationary uncle. The child is stationary after the collision. Calculate the mass of the uncle, if the magnitude of his velocity is 2.30 m s^{-1} after the collision.

Thinking	Working
Recall the equation for kinetic energy.	$E_k = \frac{1}{2}mv^2$
The collision is elastic, so the uncle's kinetic energy after the collision will be the same as that of the child before the collision.	$E_{k(before)} = E_{k(after)}$ $\Sigma\frac{1}{2}mv_{before}^{\ 2} = \Sigma\frac{1}{2}mv_{after}^{\ 2}$
Substitute in the values.	$\frac{1}{2} \times 35 \times 4^2 = \frac{1}{2} \times m_{uncle} \times 2.30^2$ $280 = \frac{1}{2} \times m_{uncle} \times 2.30^2$
Rearrange the equation to make the uncle's mass the subject.	$m_{uncle} = \frac{2 \times 280}{(2.30)^2}$
State the answer with appropriate units.	$m_{uncle} = 106\,\text{kg}$

➤ Try yourself 8.4.2

CALCULATING ELASTIC COLLISIONS

A 20.0 kg object moving at 20.0 m s^{-1} collides with a stationary 20.0 kg object and stops; the collision is elastic. Calculate the speed of the second object after the collision.

Worked example 8.4.3

CALCULATING INELASTIC COLLISIONS

A 60.0 kg gymnast is bouncing on a trampoline. The efficiency of the trampoline is 50.0%, which means his kinetic energy immediately after the bounce will be 50% of his kinetic energy immediately before the bounce. If the initial velocity of the gymnast is 5.0 m s^{-1} downwards as he hits the trampoline, calculate his speed straight after the bounce.

Thinking	Working
Recall the equation for kinetic energy.	$E_k = \frac{1}{2}mv^2$
The collision is inelastic, so the gymnast's kinetic energy after the bounce will be less than his initial kinetic energy. Calculate his kinetic energy before the bounce.	$E_{k(before)} = \frac{1}{2} \times 60.0 \times 5.0^2$ $= 750$ J
Calculate his kinetic energy after the bounce, given that the trampoline is 50.0% efficient.	$E_{k(after)} = 750 \times 0.50$ $= 375$ J
Calculate his speed after the bounce. Note that speed is requested, so no direction is necessary.	$v = \sqrt{\frac{2E_k}{m}}$ $= \sqrt{\frac{2 \times 375}{60.0}}$ $= 3.5$ m s^{-1}

➤ Try yourself 8.4.3

CALCULATING INELASTIC COLLISIONS

A physics student performs an experiment to test the efficiency of a bouncy rubber ball when it is bounced on the ground. The student finds the bounce to be 60.0% efficient; it retains 60.0% of its kinetic energy when it bounces. If the mass of the ball is 100.0 g, and the speed of the ball after the bounce is 3.0 m s^{-1}, calculate the speed of the ball immediately before the bounce.

8.4 Review

SUMMARY

- Energy is not created or destroyed; it is conserved.
- Energy may be transformed as heat, sound and other forms of energy that no longer have the ability to do mechanical work on the original object.
- The mechanical energy of an object is the sum of its kinetic and potential energy: total energy = $E_k + E_p$
- Collisions in which kinetic energy is conserved are described as elastic collisions.
- In an elastic collision: $\sum \frac{1}{2}mv^2_{before} = \sum \frac{1}{2}mv^2_{after}$
- Collisions in which some or all of the original kinetic energy is lost as heat, sound or deformation of the objects are called inelastic collisions.
- In any energy transformation, some energy is usually wasted as heat, sound and other forms of energy.

KEY QUESTIONS

Describe

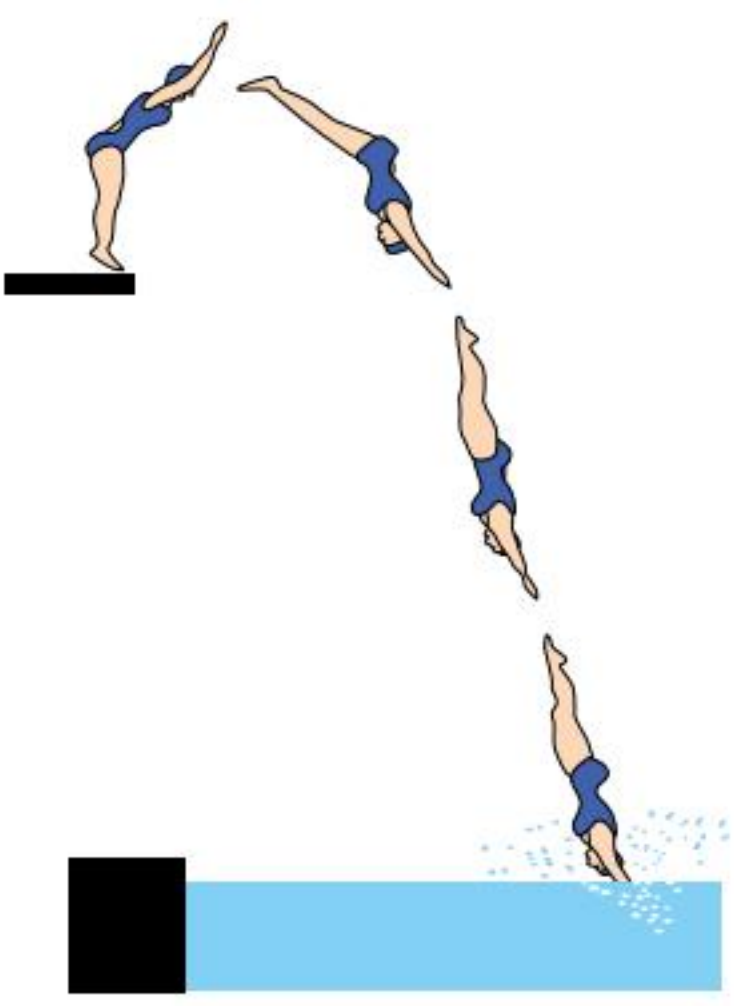
1 Describe the concept of conservation of energy for isolated mechanical systems.

2 Describe a perfectly elastic collision.

Apply

3 Describe the energy transformations a tennis ball undergoes as the ball is dropped from the player's hand.

4 The figure below shows a diver jumping off a dive board.



a Describe the energy transformations that take place from the time the diver pushes off from the board until she reaches the water.

b Sketch a graph of kinetic energy-time from the time she leaves the board until she has plunged into the water. Show the points where she reaches the maximum height achieved and when she goes below the surface of the water.

Analyse

5 A piano with a mass of 180 kg is pushed off the roof of a five-storey apartment block. The piano falls 3.0 m for each storey – a total of 15 m.

a Calculate the piano's kinetic energy as it hits the ground.

b Calculate the piano's kinetic energy as it passes the windows on the second floor, having fallen 10.0 m.

6 A branch falls from a tree and hits the ground with a speed of 5.4 m s^{-1}. Calculate the height from which the branch fell.

7 When moving around on the Moon, astronauts find it easier to use a series of small jumps rather than to walk. If an astronaut (with a mass of 120 kg including equipment) jumps to a height of 10.0 cm on the Moon, where the gravitational field strength is 1.6 m s^{-2}, calculate roughly how much her potential energy increases.

8 A white billiard ball moving at a speed of 5.00 m s^{-1} strikes a stationary red billiard ball. After the collision, the white ball continues in the same direction at a speed of 1.00 m s^{-1}. The red ball rolls ahead of it (in the direction of the white ball's initial motion) at a speed of 4.00 m s^{-1}. Each ball has a mass of 160 g. Determine the energy of the objects both before and after the collision, and state whether it was elastic or inelastic.

9 A rubber ball is dropped from a height of 1.5 m and loses 20.0% of its mechanical energy as it hits the ground. Determine the height of the rebound.

8.5 Power

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state that power is the rate at which work is done
- calculate the power being expended when a given amount of work is done in a given time
- correctly use the SI unit for power, the watt (W)
- calculate work done by a force acting at a particular velocity
- interpret energy–time graphs to calculate power being expended.

Imagine running up a set of stairs. You would do the same amount of work as if you had walked up the stairs instead. Recall from Module 8.2 that $W = \Delta E = mg\Delta h$. The work done depends on your mass and the height to which you climb, not on how quickly you make the ascent. However, the power you apply *does* depend on the time it takes to climb the stairs. When you run up the stairs, the energy change occurs at a faster rate, so your power output is greater than when walking, as shown in Figure 8.5.1.

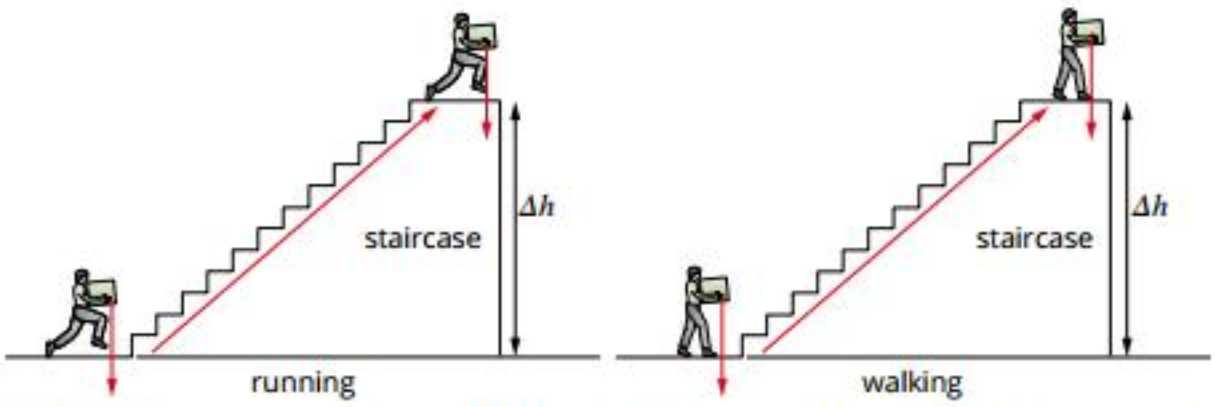


FIGURE 8.5.1 The runner and the walker both do the same amount of work, but the power output of the runner is higher than that of the walker.

CALCULATING POWER

Power is a measure of the rate at which work is done or energy is transformed. In other words, power is the work done, W, or energy transformed, ΔE, in a fixed period of time, t. This may be expressed as:

$$P = \frac{W}{t} = \frac{\Delta E}{t}$$

The unit of power is named after the Scottish engineer James Watt, who is most famous for inventing the steam engine. One watt (W) is defined as a rate of work of one joule per second; in other words:

$$1\,\text{W} = \frac{1\,\text{J}}{1\,\text{s}} = 1\,\text{J s}^{-1}$$

$P = \frac{W}{t}$

where

P is the power (W)

W is the work done (J)

t is time (s)

Worked example 8.5.1

CALCULATING POWER AS THE RATE OF CHANGE OF ENERGY

An accelerating speedboat changes its kinetic energy from 280 kJ to 970 kJ over 30.0 s. Calculate the power used for this acceleration.	
Thinking	**Working**
Recall the equation for power.	$P = \frac{W}{t} = \frac{\Delta E}{t}$
Calculate the change in the kinetic energy of the boat.	$W = \Delta E = E_{final} - E_{initial}$ $= 970 - 280$ $= 690\,\text{kJ} = 690\,000\,\text{J}$
Substitute the values into the equation for power.	$P = \frac{\Delta E}{t}$ $= \frac{690\,000}{30.0}$
State the answer with appropriate units.	$P = 23\,000\,\text{W}$ $= 23\,\text{kW}$

➤ Try yourself 8.5.1

CALCULATING POWER AS THE RATE OF CHANGE OF ENERGY

A drone flying upwards increases its gravitational potential energy by 76 J over 3.8 s. Calculate the power expended.

When work is done on an object, a force may be applied to keep it moving at a constant speed, such as when pushing a wardrobe across a carpeted floor or driving a car at the designated speed limit. In these situations, the power being applied can be calculated directly from the force applied and the speed of the object:

$$P = \frac{W}{t} \text{ and } W = Fs$$

$$P = \frac{Fs}{t} = F \times \frac{s}{t}$$

Recall that $\frac{s}{t}$ is the definition of average speed, v_{av}, so the power equation can be written as:

$$P = Fv_{av}$$

where P is power (W), F is force (N) and v_{av} is the average speed (m s^{-1}).

Worked example 8.5.2

CALCULATING POWER USING FORCE AND SPEED

A motorcycle racing at a speed of 216 km h^{-1} requires a force of 2800 N to maintain its velocity. Determine how much power its engine is expending.

Thinking	Working
Convert the motorcycle's speed to m s^{-1}.	$216\ \text{km h}^{-1} = \frac{216\ \text{km}}{1\ \text{h}} = \frac{216000\ \text{m}}{3600\ \text{s}} = 60\ \text{m s}^{-1}$
Recall the equation for power in terms of force and speed.	$P = Fv_{av}$
Substitute the values into the equation.	$P = 2800 \times 60$
State the answer with appropriate units.	$P = 168\,000\ \text{W} = 168\ \text{kW} = 170\ \text{kW}$ (to 2 significant figures)

➤ Try yourself 8.5.2

CALCULATING POWER USING FORCE AND SPEED

Calculate the power expended when a cyclist exerts a force of 17 N to travel at an average speed of 22 m s^{-1}.

POWER AND ENERGY–TIME GRAPHS

Power can also be calculated from an energy–time graph such as the one in Figure 8.5.2. The gradient of any graph (or tangent to the curve, as shown here) is $\frac{\text{rise}}{\text{run}} = \frac{\Delta E}{t}$. Since $P = \frac{W}{t} = \frac{\Delta E}{t}$, the gradient of an energy–time graph will give us the power.

This can also be seen from the equation for a straight line, $y = mx + c$, where m is the gradient. Rearranging the power equation to make ΔE the subject gives $\Delta E = Pt$. Therefore, the energy–time graph has a gradient of P.

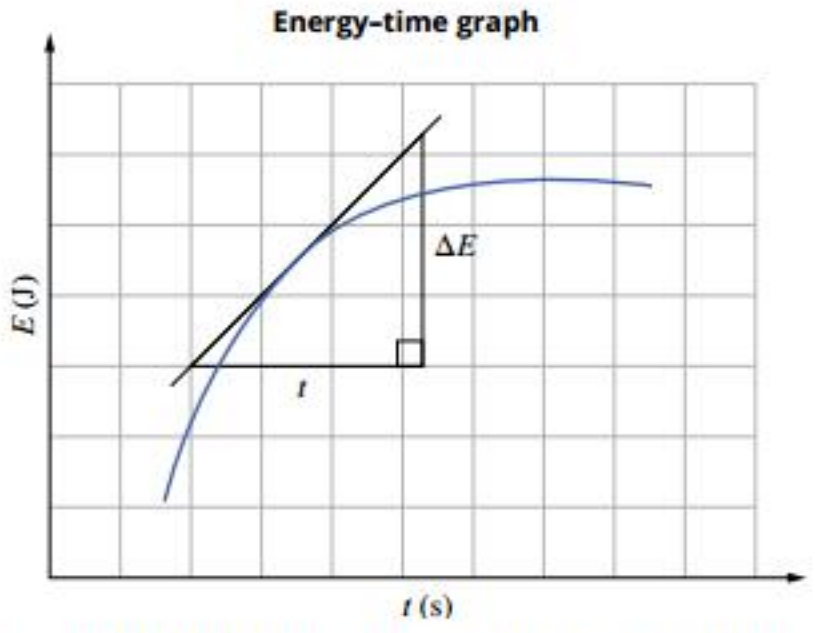
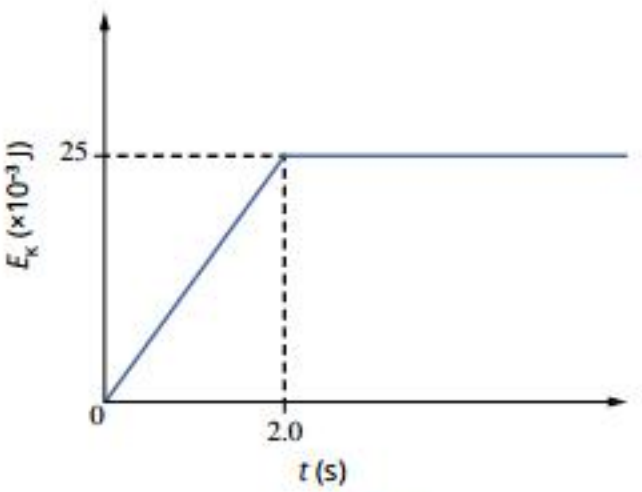


FIGURE 8.5.2 The gradient (slope) of an energy–time graph gives the power being expended at a moment in time.

Worked example 8.5.3

CALCULATING POWER AS THE RATE OF CHANGE OF ENERGY FROM AN ENERGY–TIME GRAPH

Consider the energy-time graph from Figure 8.3.2, in Module 8.3. Calculate the power applied to the cart by the force during the 2.0 seconds it acted on the cart.

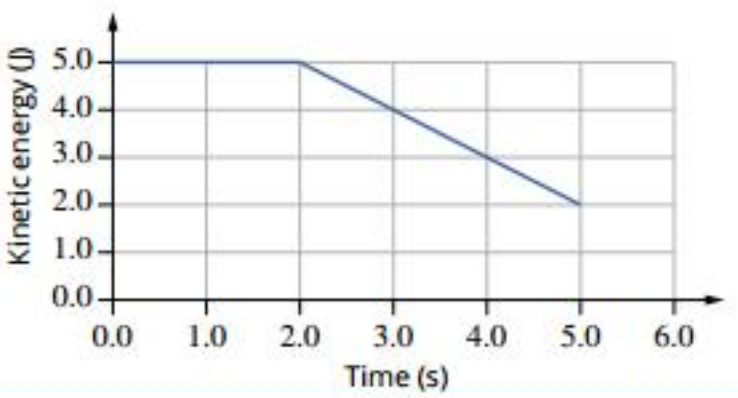


Thinking	Working
Recall that power is the gradient of an energy–time graph or recall the equation for power.	$P = \frac{W}{t} = \frac{\Delta E}{t}$
Substitute values from the graph to find ΔE and Δt.	$P = \frac{25 \times 10^{-3}}{2}$
State the answer with appropriate units.	$P = 1.25 \times 10^{-3}$ W

➤ Try yourself 8.5.3

CALCULATING POWER AS THE RATE OF CHANGE OF ENERGY FROM AN ENERGY–TIME GRAPH

A metal weight of mass 200 g is sliding across a horizontal surface as shown in the graph. Part of the surface is frictionless, part is rough. Calculate the power lost over the rough surface.



8.5 Review

SUMMARY

- Power is the rate at which work is done or energy is converted: $P = \frac{W}{t}$
- The SI unit of power is the watt (W).
- The gradient of an energy–time graph is a measure of the power expended.
- Power can also be calculated as the product of force and speed: $P = Fv_{av}$

KEY QUESTIONS

Describe

1 Describe the concept of power and state the SI unit used to measure it.

Apply

2 Explain how the power being expended can be determined from an energy–time graph.

Analyse

3 A 1610 kg car accelerates from zero to 100.0 km h^{-1} in 5.50 s. Calculate its average power output over this time.

4 A locomotive engine applies a force of 4.0 kN to keep a train moving at 20.0 m s^{-1}. Calculate the power output of the engine.

5 A 1700 kg car's engine uses 40.0 kW of power to maintain a constant speed of 80.0 km h^{-1}. Calculate the force being applied by its engine.

6 The motor of a crane has a maximum power output of 25 kW. Determine the average speed at which it can lift a concrete slab with a mass of 500.0 kg.

7 A crane can lift a load of 5.0 tonnes vertically 20.0 m in 5.0 s. Determine the approximate power of the crane.

8 If the engine of a 1400 kg car uses 25 kW to maintain an average speed of 17 m s^{-1}, calculate how much friction is acting on the car.

9 A force of 100 N is applied to move a cart 5.0 metres in 10 seconds. Calculate the work done and the power output.

Chapter review

08

KEY TERMS

elastic collision
gravitational potential energy
inelastic collision
kinetic energy
law of conservation of energy
mechanical energy
mechanical work
power
transform
work
work–energy theorem

KEY QUESTIONS

Describe

1 State the formula used to calculate the gravitational potential of an object with mass *m* that is *h* metres above the chosen zero point.

2 Identify the term used to describe a collision in which kinetic energy is conserved from the following options.

A Inelastic collision
B Elastic collision
C Gravitational collision
D Mechanical collision

3 Identify the term that describes the gradient of an energy–time graph.

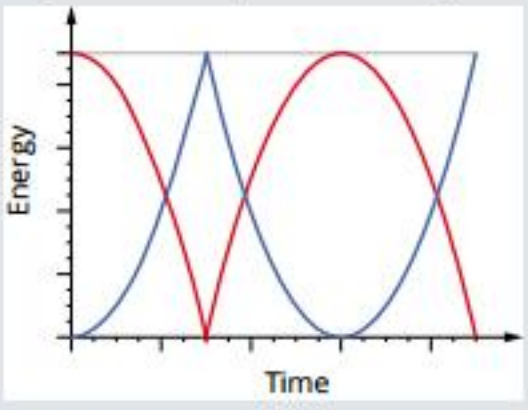
A Power
B Kinetic energy
C Potential energy
D velocity of the object

Apply

4 The speed of an object is doubled. Which of the following options best describes the effect on the magnitude of its kinetic energy.

A The kinetic energy stays the same
B The kinetic energy is doubled
C The kinetic energy is tripled
D The kinetic energy is quadrupled

5 The figure below is an energy–time graph for an object's vertical motion. The red line represents the change in gravitational potential energy over time.



a Identify the quantities represented by the blue and red lines on the graph.

b What is the significance of the constantly changing gradient for the gravitational potential energy?

Analyse

6 A rock of mass 3 kg is dropped from a height of 5 m. Assuming no air resistance, what will be the kinetic energy of the rock just before it hits the ground?

A 3 J **B** 5 J
C 15 J **D** 147 J

*The following information relates to questions **7 and 8**.*

An object of mass 2 kg is fired vertically upwards with an initial kinetic energy of 100 J. Assume no air resistance.

7 What is the speed of the object in $m s^{-1}$ when it first leaves the ground?

A 5 **B** 10
C 20 **D** 100

8 Which of the following is the best approximation of the maximum height in metres that the object will reach?

A 5 **B** 10
C 20 **D** 100

9 A car drives at a constant speed for 80.0 m. To overcome friction, its engine applies a force of 2000.0 N. Calculate the work done by the engine.

10 A person walks up a flight of 12 stairs. Each step is 240 mm long and 165 mm high. If the person has a mass of 60.0 kg and $g = 9.8 m s^{-2}$, calculate the total amount of work done against gravity.

11 If 4000.0 J is used to lift a 50.0 kg object with a constant velocity, calculate the theoretical maximum height to which the object can be raised.

12 A cricket ball with a mass of 160 g is thrown horizontally with a speed of $150 km h^{-1}$. Calculate the kinetic energy of the cricket ball at the point of release.

13 A plumber (88.0 kg) digs a ditch 40.0 cm deep. Calculate the change in the plumber's gravitational potential energy when he steps from the ground down into the ditch.

14 If the engine of a 1400 kg car uses a force of 15 kN to maintain an average speed of $17 m s^{-1}$, calculate the frictional force acting on the car.

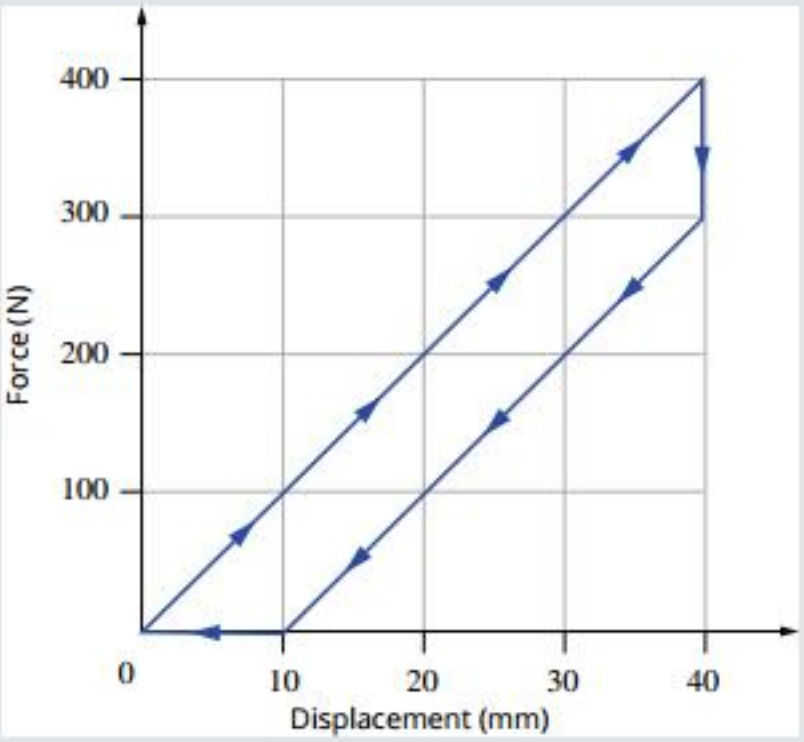
15 At the start of a 100.0 m race, a runner with a mass of 60.0 kg accelerates from a standing start to 8.0 $m s^{-1}$ in a distance of 20.0 m.

a Calculate the average force that the runner's legs apply over this distance.

b Calculate the work done by the runner's legs.

16 In high jumping, the kinetic energy of an athlete is transformed into gravitational potential energy as the athlete rises over the bar. Determine the minimum vertical speed an athlete must achieve when leaving the ground to lift their center of gravity 1.8 m high.

17 The diagram below is a simplified representation of the forces acting on a basketball when it bounces. The upwards arrows show the force as the surface of the basketball is displaced (compressed) and the downwards arrows show the force as it rebounds.



a Calculate the work done on the basketball when it compresses by 40 mm.

b Calculate the work done by the ball as it decompresses from a compression of 40 mm.

c Explain why your answers to parts a and b are different.

Interpret

18 A football with a mass of 0.43 kg is kicked off the ground with a speed of 16 $m s^{-1}$. Calculate the speed of the ball when it hits the crossbar, which is 2.44 m above the ground.

19 A thrown stone of mass 110 g strikes a piece of plasticine of mass 3.5 kg hanging from a string with speed v and becomes embedded in the plasticine. When the plasticine swings back, its height increases by 0.25 m.

Assume that the initial gravitational potential energy of the plasticine was zero (choose its starting height as the zero point for gravitational potential energy).

a Calculate the gravitational potential energy of the plasticine at the top of its swing.

b Determine the kinetic energy of the plasticine when the stone was first embedded in it.

c Calculate the speed of the plasticine when it started to swing.

Data analysis

DATA SET 1

The information below applies to Questions 1–4.

A group of students set up the apparatus shown in Figure 1 to compare the total work done on an object with the change in kinetic energy of the object.

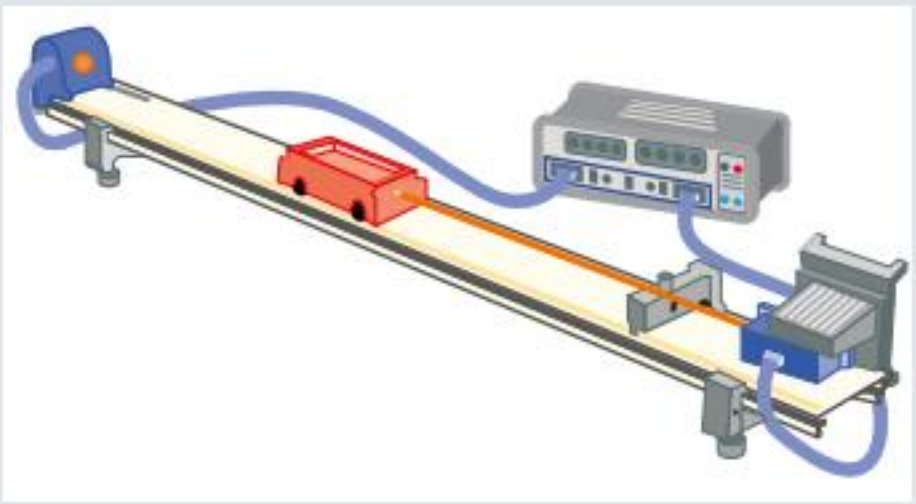


FIGURE 1 Apparatus for investigating work and energy

A force sensor is used to measure the variable force applied to the cart by a spring. A motion sensor is used to measure the velocity of the cart as it is pulled by the spring. The cart is held at the far end of the track and then released so that the spring pulls the cart along the track towards the motion sensor. Results for three trials are given in Table 1. The displacement is measured from the force sensor. The end stop is 0.200 m from the force sensor.

TABLE 1 Data obtained from three trial runs using a relatively weak spring

Displacement s (m) ±0.001 m	Force F (N) ±0.03 N			Average F (N)	Absolute uncertainty in F
	Trial 1	Trial 2	Trial 3		
0.600	1.27	1.26	1.26	1.26	±0.01
0.550	1.06	1.09	1.11	1.09	±0.03
0.500	0.90	0.87	0.84	0.87	±0.03
0.450	0.76	0.72	0.68		
0.400	0.52	0.48	0.56	0.52	±0.04
0.350	0.35	0.43	0.39	0.39	±0.04
0.300	0.18	0.22	0.26	0.22	±0.04
0.250	0.07	0.08	0.13	0.09	±0.03
0.200	0.02	0.03	0.03	0.03	±0.01

Question 1 (1 mark)

Calculate the average force (N) for the displacement of 0.450 m to 2 decimal places.

Question 2 (1 mark)

Determine the absolute uncertainty of the mean for the force, F, for the displacement of 0.450 m to 2 decimal places.

Use the formula: uncertainty $= \pm \dfrac{(x_{max} - x_{min})}{2}$

Question 3 (2 marks)

Identify the relationship between the force, F, and the displacement for this particular spring. Use evidence from Table 1 to support your answer.

Question 4 (2 marks)

Assuming the spring is long enough, predict the magnitude of the force applied by the spring when the displacement is 0.80 m.

CHAPTER

09 Properties of waves

Have you ever watched ocean waves heading towards the shore? For many people, their first thought when encountering a topic called 'waves' is to picture a water wave moving across the surface of an ocean. The wave may be created by some kind of disturbance such as the action of wind on water or a boat as it moves through the water.

Waves are, in fact, everywhere. Sound, visible light, radio waves, waves in the string of an instrument, the wave of a hand, the 'Mexican wave' at a stadium and the recently discovered gravitational waves all are waves or wave-like phenomena. Understanding the physics of waves provides a broad base on which to build your understanding of the physical world. A knowledge of waves introduces the concepts that describe the nature of light.

Syllabus subject matter

WAVE PROPERTIES

- Describe the transfer of energy through waves. **9.1**
- Describe the concept of mechanical waves. **9.1**
- Compare transverse waves and longitudinal waves. **9.2**
- Describe examples of transverse and longitudinal waves, such as sound, seismic waves and vibrations of stringed instruments. **9.2**
- Describe the concepts of compression, rarefaction, crest, trough, displacement, amplitude, period, frequency, wavelength and velocity and identify them on graphical and visual representations of a wave. **9.1, 9.2**
- Analyse the amplitude, period, frequency and wavelength from graphs of transverse and longitudinal waves. **9.2**
- Solve problems involving the wavelength, frequency, period and velocity of a wave using $v = f\lambda$ and $f = \frac{1}{T}$. **9.1**
- Describe the concepts of reflection, refraction, diffraction and superposition. **9.3, 9.4, 9.5, 9.6**
- Explain phenomena related to reflection and refraction using the wave model of light. **9.3, 9.4**
- Describe the reflection and refraction of a wave at a boundary between two media. **9.3, 9.4**
- Explain constructive interference and destructive interference of two simple waves. **9.6**
- Determine the resultant amplitude of two simple waves interacting using the principle of superposition. **9.6**
- Explain the formation of standing waves in terms of superposition with reference to constructive and destructive interference, and nodes and antinodes. **9.7**

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9.1 Describing a wave

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe that waves transfer energy
- recall examples of waves
- describe mechanical waves
- identify the amplitude and wavelength from a displacement–distance graph
- identify the amplitude and period from a displacement–time graph
- relate the period to the frequency using the inverse relationship $f = \frac{1}{T}$
- solve problems involving wavelength, frequency, period and velocity using $v = f\lambda$.

FIGURE 9.1.1 The ripples in a pond indicate a transfer of energy.

Throw a stone into a pool or lake, and you will see circular waves form and move outwards from the source as ripples, as shown in Figure 9.1.1. Stretch a cord out on a table and wriggle one end back and forth across the table surface and another type of wave can be observed. Sound waves, water waves and waves in strings are all examples of **mechanical waves**. Mechanical waves, as opposed to electromagnetic waves, cannot transmit energy through a vacuum. Mechanical waves are the focus of this chapter.

MECHANICAL WAVES

Watch a piece of driftwood, a leaf, or even a surfer, resting in the water as a smooth wave goes past, and you will notice that the object moves up and down but does not move forwards with the wave. The movement of the object on the water reveals how the **particles** in the water move. As the wave passes, the particles in the water move up and down from an average position.

Any wave that needs a **medium** (such as water or air particles) through which to travel is called a mechanical wave. Mechanical waves can move over very large distances, but the particles of the medium only have very limited movement.

Mechanical waves transfer energy from one place to another through a medium. The particles of the matter vibrate back and forth or up and down about an average position, which transfers the energy from one place to another. For example, energy is given to an ocean wave by the action of the wind far out at sea. The *energy* is transported by waves to the shore but (except in the case of a tsunami event) most of the ocean water itself does not travel onto the shore.

A wave involves the transfer of energy without the net transfer of matter.

PULSES VERSUS TRAVELLING WAVES

A single wave **pulse** can be formed by giving a slinky spring or rope a single up-and-down motion, as shown in Figure 9.1.2a. As the hand pulls upwards, the adjacent parts of the slinky will also feel an upwards force and begin to move upwards. The source of the wave energy is the movement of the hand.

If the up-and-down motion is repeated, each successive section of the slinky will move up and down, moving the wave forwards along the slinky as a travelling wave, as shown in Figure 9.1.2b. Connections between each loop of the slinky cause the wave to travel away from the source, carrying with it the energy from the source.

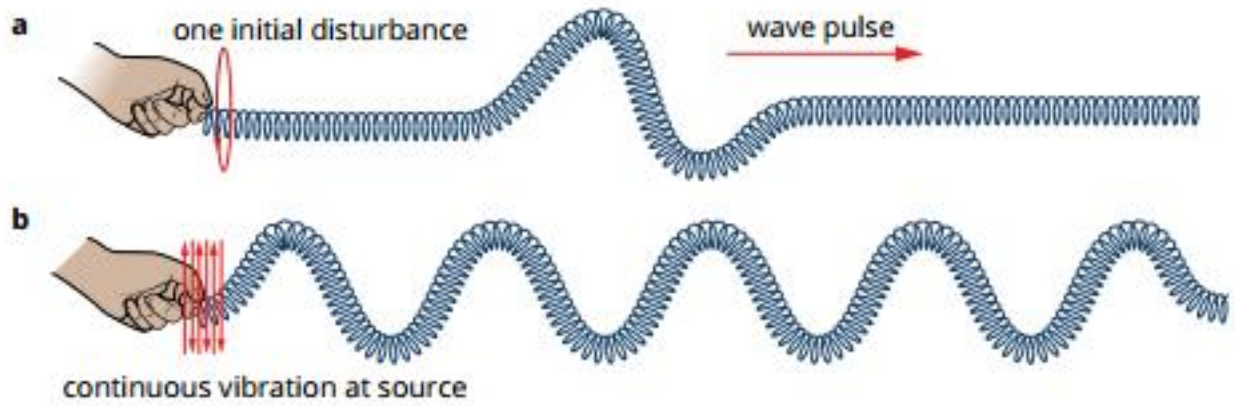


FIGURE 9.1.2 (a) A single wave pulse can be sent along a slinky by a single up-and-down motion. (b) A continuous or travelling wave is created by a regular, repeated movement of the hand.

In a continuous wave or **travelling wave**, continuous vibration of the source will cause the particles within the medium to oscillate about their average position in a regular, repetitive or periodic pattern. This is shown in Figure 9.1.2b. The source of any mechanical wave is this repeated motion or vibration. The energy from the vibration moves through the medium and constitutes a mechanical wave.

MEASURING MECHANICAL WAVES

The features of a mechanical wave can be represented using a graph. In this section you will explore how the displacement of particles within the wave can be represented using graphs. From these graphs, several key features of a wave can be identified:

- amplitude
- wavelength
- frequency
- period
- speed.

Waves of different amplitudes and wavelengths can be seen in Figure 9.1.3.

FIGURE 9.1.3 Waves have different wavelengths, amplitudes, frequencies, periods and velocities.

Displacement–distance graphs

Figure 9.1.2b shows a continuous wave in a slinky. This 'snapshot' in time shows the particles moving up and down about a central rest position. This is called a **sinusoidal oscillation**. As a wave passes a given point, the particle at that point will go through a complete cycle before returning to its starting point. The wave spread along the length of the slinky has the shape of a sine or cosine function, which you will recognise from mathematics. A displacement–distance graph shows the position (displacement) of the particles at any moment in time along the slinky about a central position.

The displacement–distance graph in Figure 9.1.4 shows the displacement of all particles along the length of a **transverse wave** at a particular point in time.

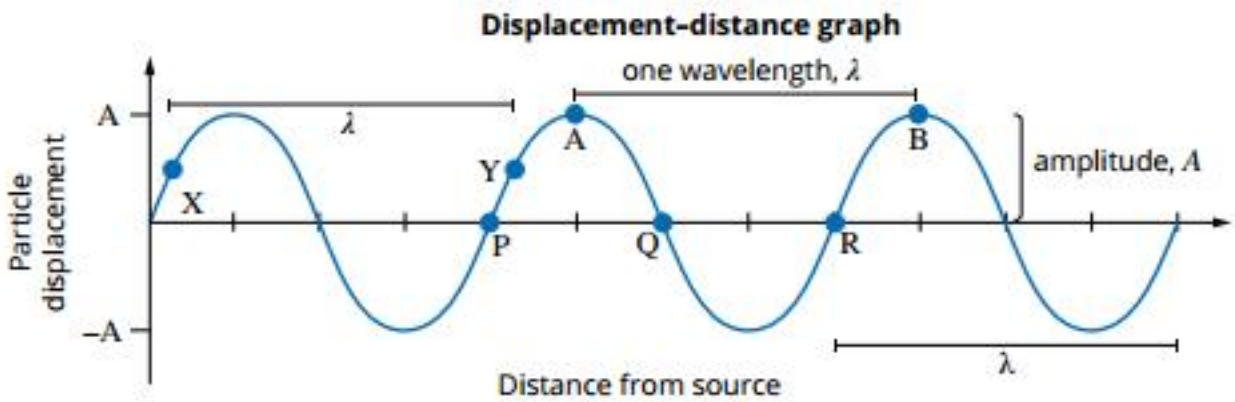


FIGURE 9.1.4 The graph shows the particle displacements along a wave.

From a displacement–distance graph, the amplitude and wavelength of a wave are easily recognisable.

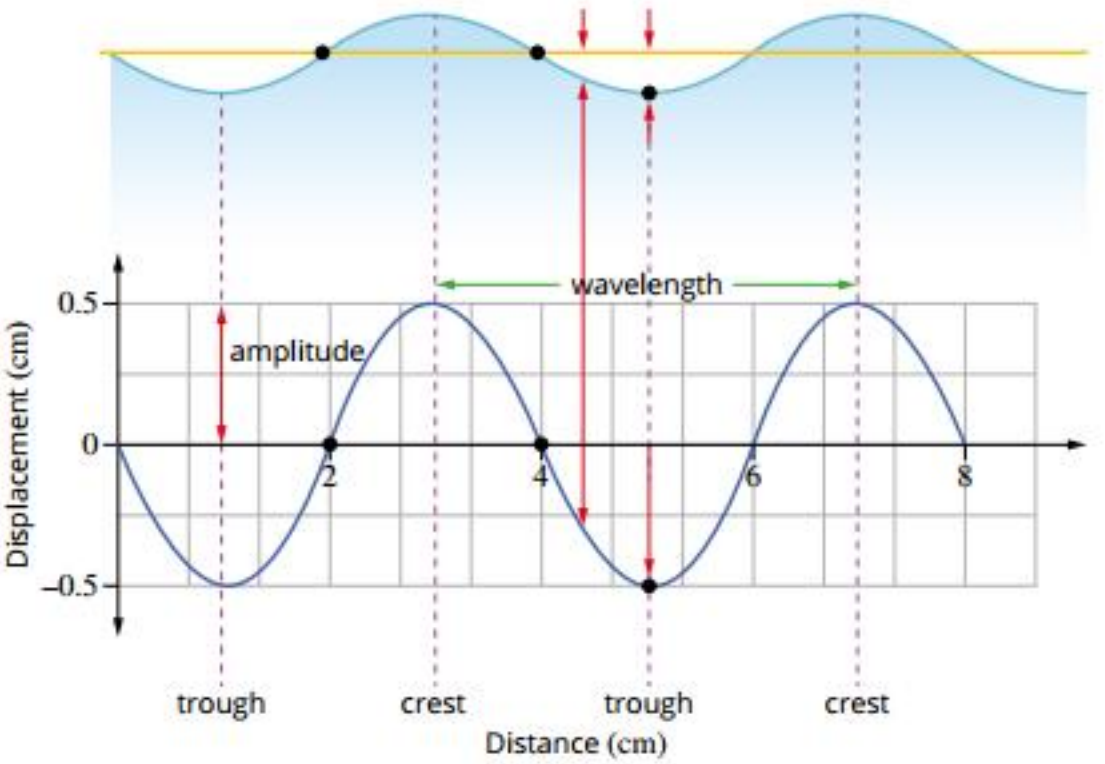
- The **amplitude** (shown as A on the vertical axis in Figure 9.1.4) of a wave is the maximum displacement of a particle from the average or rest position. That is, the amplitude is the distance from the middle of a wave to the top of a **crest** or to the bottom of a **trough**. The total distance through which a particle will move in one cycle is twice the amplitude.
- The **wavelength**, λ, of a wave is the distance between any two successive points in phase (for example, points A and B or X and Y in Figure 9.1.4). It is denoted by the Greek letter λ (lambda), and is measured in metres. Two particles on the wave are said to be in **phase** if they have the same displacements from the average position and are moving in the same direction. Points P and R in Figure 9.1.4 are two such particles that are in phase, as are points A and B and X and Y, but not P and Q.
- The **frequency**, f, is the number of complete cycles that pass a given point per second and is measured in hertz (Hz).
- The **period**, T, of a wave is the amount of time that it takes one complete cycle of the wave to pass a particular point.

By drawing a series of displacement–distance graphs at various times, you can see the motion of the wave. By comparing the changes in these graphs, you can find the travelling speed and direction of the wave, as well as the direction of motion of the vibrating particles.

Worked example 9.1.1

DISPLACEMENT–DISTANCE GRAPH

The displacement–distance graph below shows a snapshot of a mechanical water wave as it travels to the right. Use the graph to determine the amplitude and the wavelength of this wave.



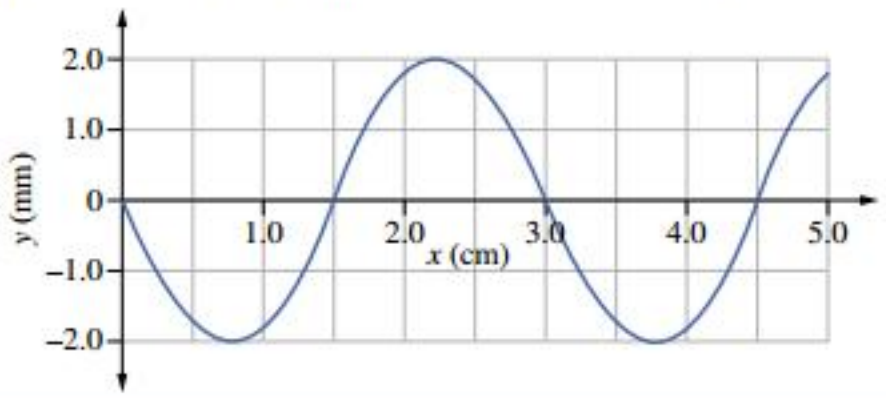
Thinking	Working
Amplitude on a displacement–distance graph is the distance from the average or rest position to a crest or a trough. Read the displacement of a crest or a trough from the vertical axis. Convert to SI units where necessary.	Amplitude = 0.5 cm = 5×10^{-3} m

Wavelength is the distance for one complete cycle. Any two consecutive points in phase and at the same position on the wave could be used. Convert to SI units where necessary.	The first cycle runs from the origin (0, 0) through a trough (1.0, –0.5), crosses the *x*-axis at (2.0, 0), up to the crest (3.0, 0.5) and then crosses the *x*-axis at (4.0, 0). The horizontal distance of one complete cycle is the wavelength. Wavelength $\lambda = 4\,\text{cm} = 4 \times 10^{-2}\,\text{m}$

➤ Try yourself 9.1.1

DISPLACEMENT–DISTANCE GRAPH

The graph below shows a snapshot of a mechanical wave as it travels along a string towards the right. The displacement, *y*, varies with the distance, *x*, as shown. Use the graph to determine the amplitude and the wavelength of this wave.



Displacement–time graphs

Figure 9.1.5 shows a displacement–time graph that tracks the position of one point over time as the wave moves through the point.

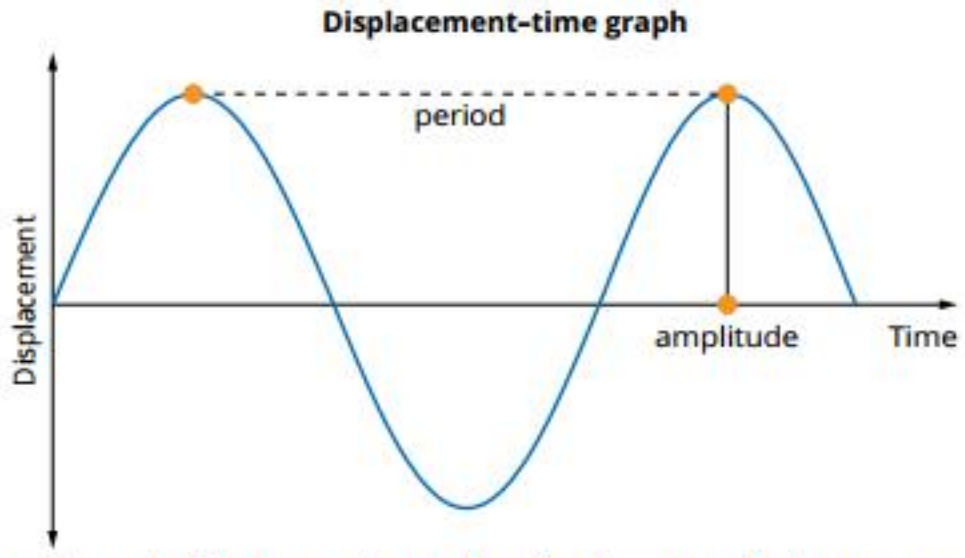


FIGURE 9.1.5 The graph of displacement versus time from the source of a transverse wave shows the movement of a single point on a wave over time as the wave passes through that point.

The displacement–time graph looks very similar to a displacement–distance graph of a transverse wave, so be careful to check the horizontal axis label.

Crests and troughs are shown the same way in both graphs. The amplitude is still the maximum displacement from the average or rest position of either a crest or a trough. But the distance between two successive points in phase in a displacement–time graph represents the period of the wave, *T*, measured in seconds.

The period, *T*, is the time it takes for any point on the wave to go through one complete cycle (for example, from crest to successive crest). The period of a wave is inversely related to its frequency, *f*.

The amplitude, frequency and period of a wave, and the direction of motion of a particular particle, can be determined from a displacement–time graph.

$f = \frac{1}{T}$

where

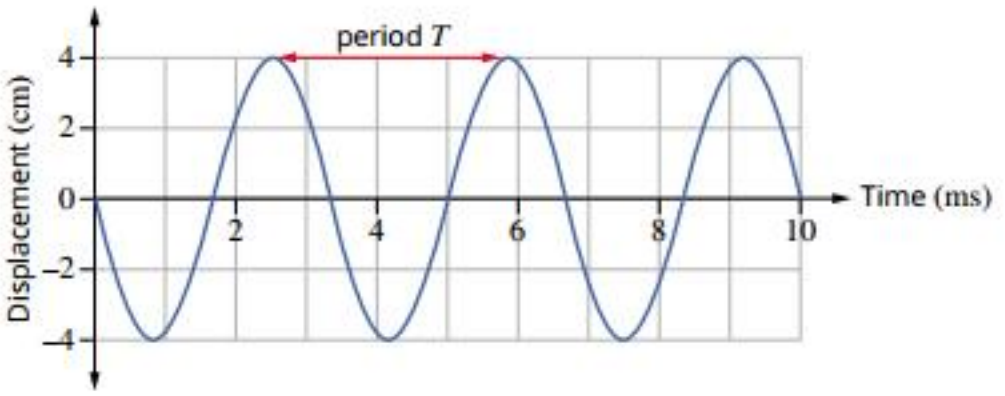
T is the period of the wave (s)

f is the frequency of the wave (Hz).

Worked example 9.1.2

DISPLACEMENT–TIME GRAPHS

The displacement–time graph below shows the motion of a single point of a rope as a wave travels to the right. Use the graph to identify the amplitude, period and frequency of the wave.

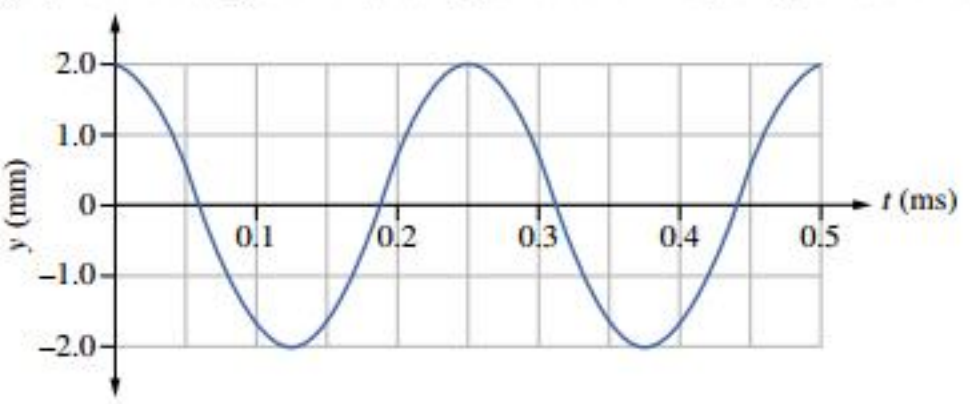


Thinking	Working
The amplitude on a displacement–time graph is the displacement from the average position to a crest or trough. Note the displacement of successive crests and/or troughs on the wave and check the units on the vertical axis. If necessary, convert to SI units.	Maximum displacement is 4 cm. Therefore, amplitude = 4×10^{-2} m.
Period is the time it takes to complete one cycle and can be identified on a displacement–time graph as the time between two successive points that are in phase. Identify the total number of oscillations on the graph. Divide the total time t by the total number of oscillations. Note, there are three troughs and three crests, or three complete oscillations in 10 ms. Where necessary, convert to SI units.	Period: $T = \frac{10}{3}$ ms $= 3.3$ ms $= 3.3 \times 10^{-3}$ s
Frequency can be calculated using $f = \frac{1}{T}$, measured in hertz (Hz).	$f = \frac{1}{T}$ $= \frac{1}{3.3 \times 10^{-3}}$ $= 300$ Hz

➤ Try yourself 9.1.2

DISPLACEMENT–TIME GRAPHS

The displacement–time graph below shows the displacement of a particle on a mechanical wave moving to the right. The displacement, y, varies with the time, t. Use the graph to identify the amplitude, period and frequency of the wave.



THE WAVE EQUATION

Although the speed of a wave can vary, there is a relationship between the speed of a wave and other significant wave characteristics. In the study of motion, speed (v) is given by:

$$v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t}$$

This can be rewritten in terms of the distance of one wavelength (λ) in one period (T): $v = \frac{\lambda}{T}$.

Using the relationship between the period and frequency $f = \frac{1}{T}$

$$v = \frac{\lambda}{T}$$
$$= \frac{\lambda}{\frac{1}{f}}$$
$$= f\lambda$$

This is known as the wave equation and applies to all types of waves.

> **The wave equation**
> $v = f\lambda$
> where
> v is the speed ($m\,s^{-1}$)
> f is the frequency (Hz)
> λ is the wavelength (m).

Worked example 9.1.3

WAVE EQUATION FREQUENCY

A mechanical wave has a wavelength of 1.5 m and a speed of 6.0 $m\,s^{-1}$. Determine the frequency, f, of the wave.	
Thinking	**Working**
The wave equation states that $v = f\lambda$. Knowing both v and λ, the frequency, f, can be found. Rewrite the wave equation in terms of f.	$f = \frac{v}{\lambda}$
Substitute the known values and solve.	$f = \frac{6.0}{1.5}$ $= 4.0\,Hz$

➤ Try yourself 9.1.3

WAVE EQUATION FREQUENCY

A mechanical wave has a wavelength of 0.5 m and a speed of 4.0 $m\,s^{-1}$. Determine the frequency, f, of the wave.

Worked example 9.1.4

WAVE EQUATION PERIOD

A mechanical wave has a wavelength of 3.0 m and a speed of 150 $m\,s^{-1}$. Calculate the period, T, of the wave.	
Thinking	**Working**
Rewrite the wave equation in terms of T.	$v = f\lambda$ and $f = \frac{1}{T}$ $v = \frac{1}{T} \times \lambda$ $= \frac{\lambda}{T}$
Substitute the known values and solve.	$T = \frac{\lambda}{v}$ $= \frac{3.0}{150}$ $= 2.0 \times 10^{-2}\,s$

➤ Try yourself 9.1.4

WAVE EQUATION PERIOD

A mechanical wave has a wavelength of 1.7×10^{-4} m and a speed of 340 $m\,s^{-1}$. Calculate the period, T, of the wave.

INTENSITY

As well as being described by their speed, frequency and amplitude, waves can be described by their **intensity**, which is a measure of their power per unit area. The power is a measure of the energy transferred by the travelling wave. Intensity is measured in units of watts per square metre ($W\,m^{-2}$).

Light waves emitted from the surface of a luminous object such as a lamp or neon sign, are of a certain intensity. Bright lights that are shone into the eyes of people (for example, when in dark locations) can be unpleasant to view. The iris and pupil of the eye take time to adjust to the sudden change in intensity entering the light-sensitive retina at the back of the eye.

Intensity applies to sound waves as well as light. The threshold of human hearing is 0 decibels, which is usually associated with sounds that can just be heard. The decibel scale is a ratio of the intensity of a noise or sound to the threshold of hearing intensity. One of the loudest sounds or sounds of highest intensity was the Krakatoa volcanic eruption, which left people with ruptured eardrums. The noise of the launch of the *Saturn V* rocket measures an amazing 220 decibels at close range, and the energy from the sound waves it produces can melt concrete. Other sound intensities are busy city traffic, which has been measured at 85 decibels, and typical speech at around 55 decibels.

The intensity of light waves is discussed further in Chapter 11.

9.1 Review

SUMMARY

- Vibrating objects transfer energy through waves, which travel outwards from the source. Examples include waves on water, waves on a string and sound waves in air.
- A wave may be a single pulse or it may be continuous or periodic (successive crests and troughs).
- A wave only transfers energy from one point to another. There is no net transfer of matter or material.
- A mechanical wave requires a medium to travel through.
- Waves can be represented by displacement–distance graphs and displacement–time graphs.
- From a displacement–distance graph, you can identify amplitude and wavelength.
- From a displacement–time graph, you can identify amplitude, frequency and period.
- The period of a wave has an inverse relationship to the frequency, according to the relationship:

$$f = \frac{1}{T}$$

- The speed of a wave can be calculated using the wave equation:

$$v = f\lambda = \frac{\lambda}{T}$$

- The intensity of a wave is a measure of its power per unit area.

KEY QUESTIONS

Describe

1 Recall at least five waves or wave-like phenomena.

2 Recall what all waves transfer.

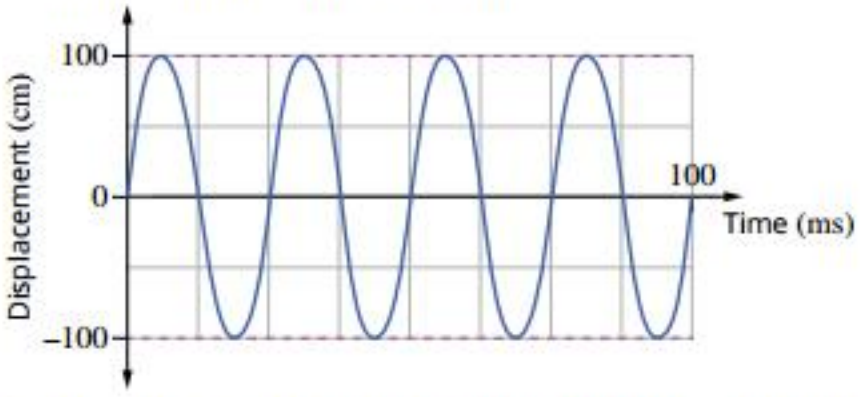
3 Describe a mechanical wave.

Apply

4 At a K-pop concert, sound waves are emitted from a speaker. Max sits in a seat 25 m away from the speaker. He turns to his friend and makes some statements about the sound he is hearing. Identify the correct statements below. Justify the correct statements with an explanation.

- **a** The air particles carried the energy as they travelled from the speaker to me.
- **b** Energy has been transferred from the speaker to me due to the oscillation of the air particles.
- **c** The air particles transfer the energy as they oscillate about an average rest position; the particles do not have any net movement.

5 The displacement–time graph below is for a particle on a mechanical wave. Determine the amplitude, period and frequency of the wave.



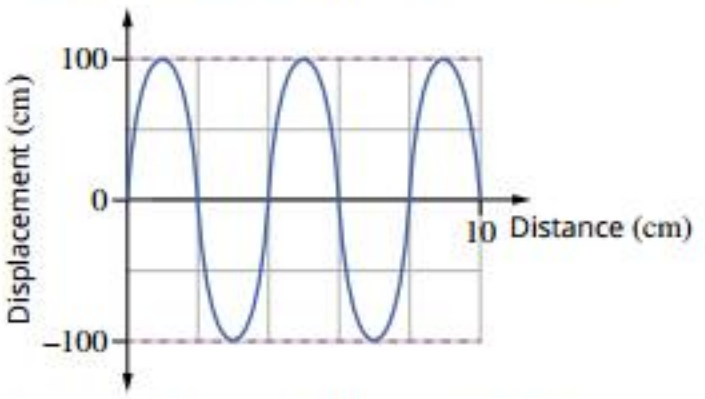
6 Draw a wave on a suitable graph with an amplitude of 5 m and a wavelength of 2 m.

Analyse

7 Determine the speed of a wave with a wavelength of 2 m and a frequency of 15 Hz.

8 Calculate the period of a wave with a speed of 45 $m s^{-1}$ and a wavelength of 3.0 m.

9 The displacement–distance graph for a mechanical wave at an instant in time is shown below. Determine the wavelength and amplitude of this wave.



10 A wave has a period of 2.0×10^{-3} s (2.0 ms). Calculate the frequency of this wave.

9.2 Types of waves

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe transverse waves in terms of the direction of oscillation and the direction of wave energy movement
- describe longitudinal waves in terms of the direction of oscillation and the direction of wave energy movement
- provide examples of both transverse and longitudinal waves
- compare transverse and longitudinal waves
- draw and label both transverse and longitudinal waves
- represent a travelling wave using wavefronts and a ray diagram
- represent (or draw) a longitudinal wave as a sinusoidal wave with labels for compressions and rarefactions
- analyse the amplitude, period, frequency and wavelength of longitudinal and transverse waves from their graphs
- classify everyday types of waves such as seismic waves, tsunami waves and stringed instruments as either longitudinal waves or transverse waves.

Mechanical waves are involved in many everyday experiences. Pluck a guitar string and watch the string vibrate or listen to the sound it makes. Watch the stereo speaker membrane vibrate back and forth when you play your favourite music or song. Have you ever heard the sound produced when the top of a wine glass is rubbed by a finger? Different types of mechanical waves can be observed in each of these examples.

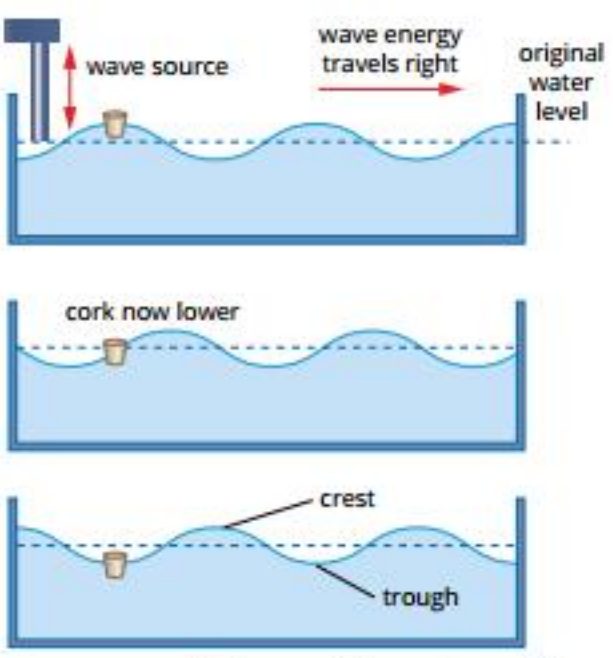


FIGURE 9.2.1 Using a cork to monitor particle displacement on a wave

TRANSVERSE AND LONGITUDINAL WAVES

Mechanical waves can be grouped into two types: transverse and longitudinal.

Transverse waves

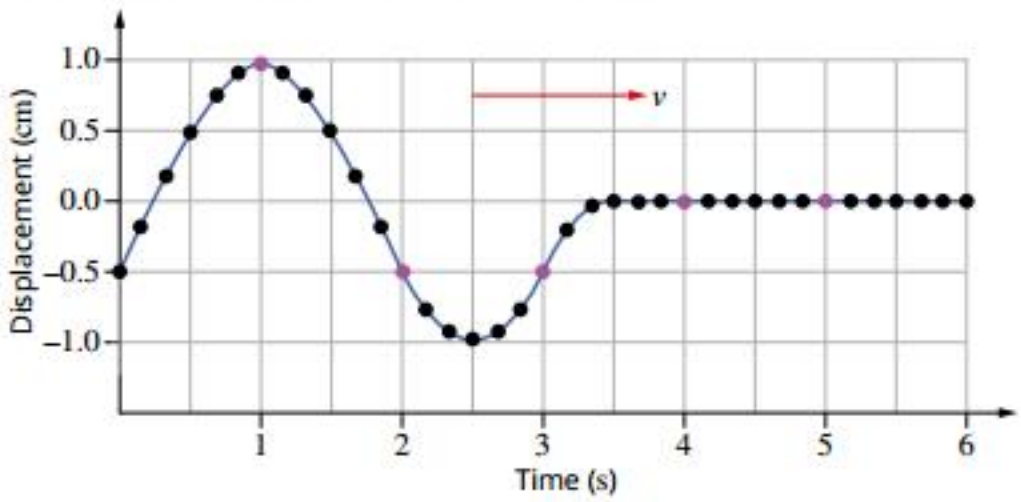
In a **transverse** mechanical wave, the wave travels in the direction of motion of the wave energy. When waves travel on water, or through a rope, spring or string, the particles within the medium vibrate up and down in a direction perpendicular, or transverse, to the direction of the wave energy. When the particles are displaced upwards from the average position, or resting position, they reach a maximum positive displacement called a crest. Particles below the average position fall to a maximum negative position called a trough, as shown in Figure 9.2.1. Note that, as a continuous water wave moves to the right, the up-and-down displacement of the particles (which is transverse to the wave motion) can be monitored using a cork. The cork simply moves up and down as the wave passes through it.

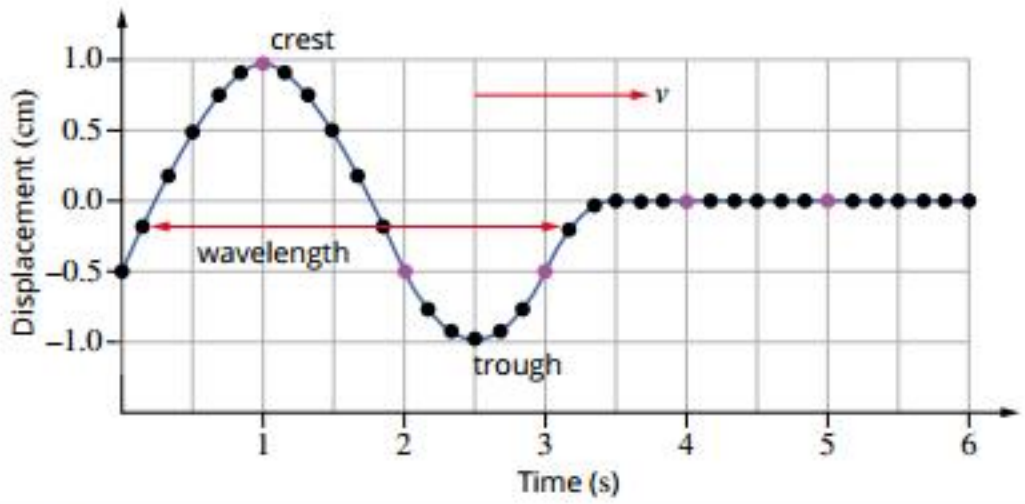
Worked example 9.2.1

TRANSVERSE WAVES

A transverse wave is shown below transferring energy to the right. The displacement (y-axis) is shown in cm, and the time (x-axis) is shown in seconds. Label the crest, the trough, and the wavelength, λ.

Determine the amplitude, frequency and period of the transverse wave.



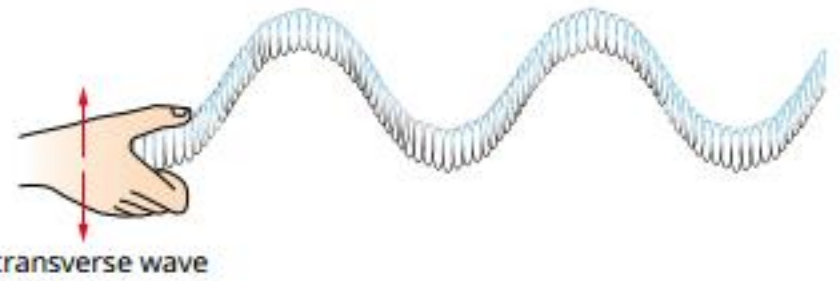
Thinking	Working
A crest is a point on a transverse wave where the particles are at a maximum positive displacement from the rest position. A trough is a point on a transverse wave where the particles are at the maximum negative displacement from the rest position. The wavelength of a transverse wave is measured from identical points, or phases, on successive waves.	
The amplitude is measured from the rest position ($y = 0.0\,cm$) to the maximum displacement ($y = 1.0\,cm$).	$A = 1.0\,cm$
The period is the time a complete wave oscillation takes to pass a given point. The particle ($y = -0.5\,cm$) moves up and down and is back at its original position ($y = -0.5\,cm$) in a time of 3.0 seconds.	$T = 3\,s$
Use the inverse relationship between frequency and period to solve for frequency f.	$f = \frac{1}{T}$ $= \frac{1}{3}$ $= 0.3\,Hz$
Write the amplitude, frequency and period of the wave. Convert to SI units when necessary.	amplitude $= 1.0 \times 10^{-2}\,m$. frequency $= 0.3\,Hz$. period $= 3\,s$.

➤ Try yourself 9.2.1

TRANSVERSE WAVES

A slinky spring is being moved up and down perpendicular to the net movement of energy, as shown in the diagram. The hand moves a total distance of 40.0 cm from the lowest point to the highest, completing one oscillation in 0.60 seconds. The transverse wave travels a length of 3.0 m in 2.8 seconds. Label the crest, the trough, and the wavelength, λ.

Determine the amplitude A, wavelength λ, frequency f, and period T.



Longitudinal waves

In a longitudinal mechanical wave, the vibrations of the particles within the medium are in the same direction, or parallel to, the direction of energy flow of the wave. You can demonstrate this type of wave with a slinky by moving your hand backwards and forwards in a line parallel to the length of the slinky, as shown in Figure 9.2.2.

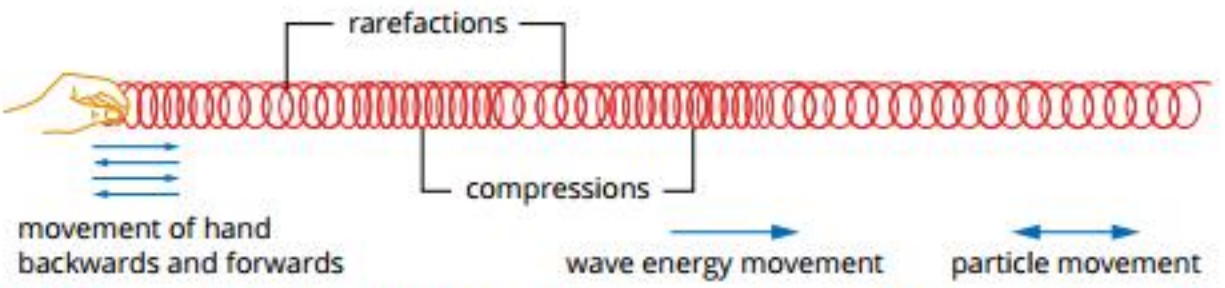


FIGURE 9.2.2 When the direction of the vibrations of the medium and the direction of travel of the wave energy are parallel, a longitudinal wave is created. This can be demonstrated with a slinky.

As you move your hand, a series of compressed and expanded areas form along the slinky. **Compressions** are those areas where the coils of the slinky come together. Expansions are regions where the coils are spread apart. Areas of expansion are termed **rarefactions**. The compressions and rarefactions in a **longitudinal wave** correspond to the crests and troughs of a transverse wave. Sound is an example of a longitudinal wave. Compressions in a sound wave, in air, are where the air particles are denser and rarefactions are where the air particles are less dense. This can be seen in Figure 9.2.3 below.

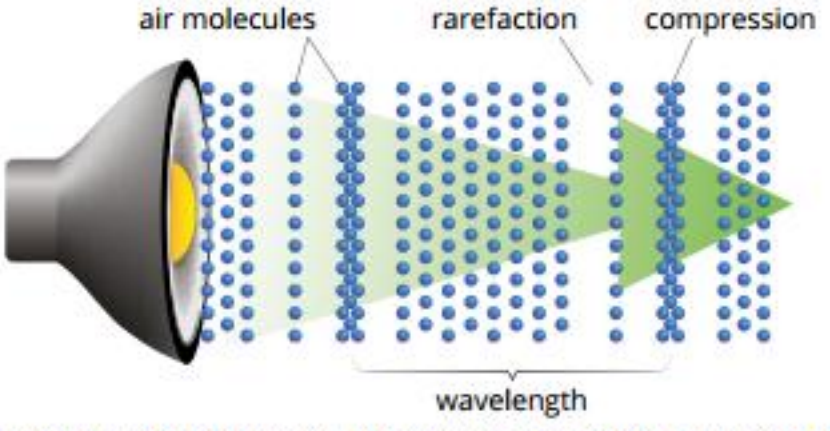


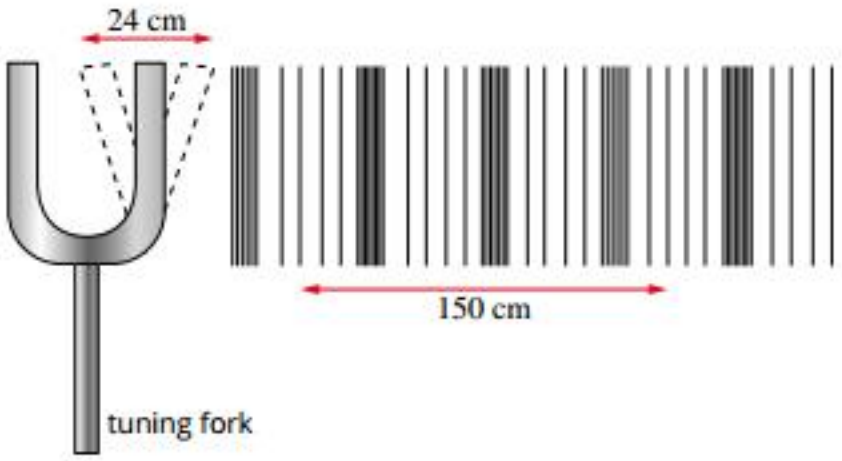
FIGURE 9.2.3 A sound wave going through air molecules as a longitudinal wave showing the compressions and rarefactions of the particles

Worked example 9.2.2

LONGITUDINAL WAVES

The diagram below shows a tuning fork producing longitudinal waves. Lines have been drawn to represent the wave instead of individual particles. The lines show areas of compression and rarefaction of air molecules. Label a compression, C, a rarefaction, R, and the wavelength, λ.

Determine the amplitude, wavelength, frequency and period of the longitudinal wave. The speed of sound in air is $340\,m\,s^{-1}$.



Thinking	Working
A compression (C) is a section where the air molecules are closer together due to greater air pressure. A rarefaction (R) is a region where the air molecules are further apart due to lower air pressure. The wavelength (λ) of a longitudinal wave is the distance between successive compressions.	
The amplitude A is the displacement from the rest position of the tuning fork leg to the maximum displacement from the rest position.	$A = 12\,cm$
The 150 cm line measures the distance from the first rarefaction to the fourth rarefaction. This is three wavelengths in length.	$\lambda = \frac{150}{3}$ $= 50\,cm$
The frequency can be calculated using the wave equation. The speed of sound in air is $340\,m\,s^{-1}$ and the wavelength is 0.50 m.	$f = \frac{v}{\lambda}$ $= \frac{340}{0.50}$ $= 680\,Hz$
The period T is the inverse of the frequency f. Convert to SI units where necessary.	$T = \frac{1}{f}$ $= \frac{1}{680}$ $= 0.0015\,s$
Write the amplitude, wavelength, frequency and period of the wave. Convert to SI units when necessary.	amplitude $= 1.2 \times 10^{-1}$ m. wavelength $= 5.0 \times 10^{-1}$ m. frequency $= 680$ Hz. period $= 1.5 \times 10^{-3}$ s.

➤ Try yourself 9.2.2

LONGITUDINAL WAVES

A slinky spring is being moved backwards and forwards parallel to the net movement of energy, as shown in the diagram. The hand moves back and forth a total distance of 20.0 cm, backwards 10.0 cm and then forwards 10.0 cm, completing one oscillation in 0.80 seconds. The longitudinal wave travels a length of 2.0 m in 0.60 seconds. Label a compression, a rarefaction, and the wavelength.

Determine the amplitude, A, wavelength, λ, frequency, f, period, T, and speed, v.

REPRESENTING WAVES

Waves are often represented with **wavefronts** and **rays** instead of the sinusoidal waveform. These lines represent information such as wavelength and the direction of net energy movement of the travelling wave, without adding any complex information such as particle vibrations or sinusoidal graphs. Both wavefronts and rays are simplified ways of drawing wave motion.

Wavefronts and rays

It is easier to sketch waves showing only the crests of a wave. As the wave passes through the medium, like ripples in a pond, you notice only the crests of the ripples. The crests on the ripples are points where the particles of the medium are in phase. You will also notice that after every crest there follows a trough, followed by another crest and so on. The distance between successive crests, or successive troughs, is called the wavelength. The wavefronts are drawn on these points (either crest to crest, or trough to trough) perpendicular to the direction of the net energy movement of the wave.

A ray is drawn in the direction of the net energy movement of the travelling wave. This is shown in Figure 9.2.4 for a plane wave (one-dimensional wave) and in Figure 9.2.5 for a three-dimensional wave. Rays are drawn perpendicular to wave fronts.

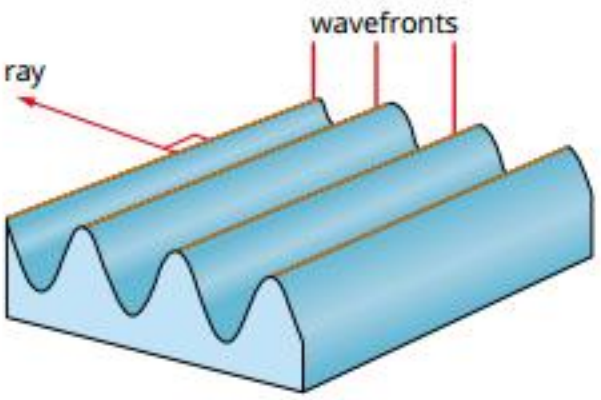


FIGURE 9.2.4 The wavefronts and the ray are shown on a plane wave with energy movement in the direction of the ray. The energy is moving in one dimension.

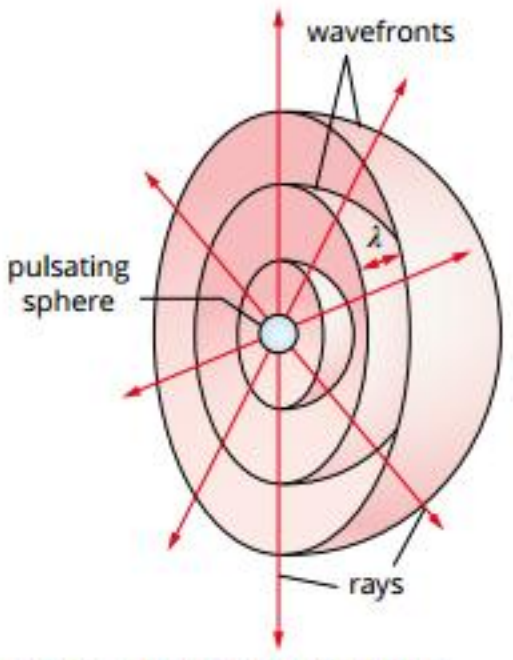


FIGURE 9.2.5 The wavefronts and rays representing three-dimensional wave energy transfer. Note the distance between the wavefronts and the symbol λ for wavelength.

EXAMPLES OF TRANSVERSE AND LONGITUDINAL WAVES

When at the beach in the surf, or when listening to a podcast, watching television, or streaming online music sites, you are dealing with waves. Examples of both transverse and longitudinal waves will be discussed further, with some examples exhibiting both transverse and longitudinal wave properties.

Sound waves

A sound wave is an important example of a longitudinal wave. As the cone of a loudspeaker vibrates, the layer of air next to it is alternately pushed away and drawn back, creating a series of compressions and rarefactions in the air (Figure 9.2.6). This vibration is transmitted through the air as a sound wave. As in transverse waves, the individual molecules vibrate over a very small distance, while the wave itself can carry energy over very long distances. If the vibration was from a single point, then the waves would tend to spread out spherically.

FIGURE 9.2.6 The motion of a flame in front of a loudspeaker is clear evidence of the continuous movement of air backwards and forwards as the loudspeaker creates a sound wave.

Seismic waves

Three main types of waves are produced by an earthquake. Primary **P-waves**, secondary **S-waves** and the **surface waves** that result from earthquakes will be covered in this module, but not the different types of earthquakes.

P-waves are compressional or longitudinal waves travelling at somewhere between 1.5–13 km s^{-1}. The ground shakes in the direction the P-waves are transferring energy, as shown in Figure 9.2.7. The P-waves are the first to be detected by seismic stations and travel through the Earth's core.

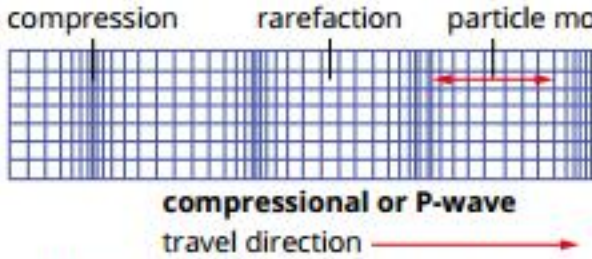


FIGURE 9.2.7 The diagram of a P-wave shows particle motion as the wave travels from left to right.

S-waves are transverse waves. They travel at around half the speed of P-waves and shake the ground in a direction perpendicular to the direction of energy movement, as shown in Figure 9.2.8. These waves do not travel through liquids such as molten material, or Earth's outer core. Seismic stations detect S-waves after P-waves.

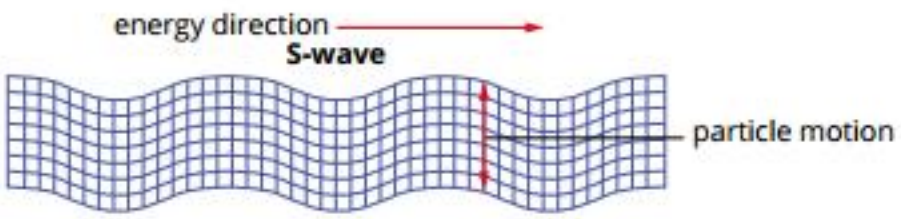


FIGURE 9.2.8 The diagram of an S-wave shows particle motion as the wave energy travels from left to right.

Surface waves travel just below or along the ground's surface and are slower than both the P-waves and S-waves. These waves have some rolling and side-to-side movement and are very damaging to built-up areas, as shown in Figure 9.2.9. Buildings experience structural damage due to these surface waves.

The three types of seismic waves are shown in Figure 9.2.9. The type of wave is shown on the left-hand side, and the effects on the Earth's crust are shown on the right-hand side. The waves are ordered top to bottom in terms of the relative speeds of each type of seismic wave. Unlike the shallow surface waves, both P-waves and S-waves penetrate deep inside the Earth and provide detail about the Earth's structure that is otherwise inaccessible.

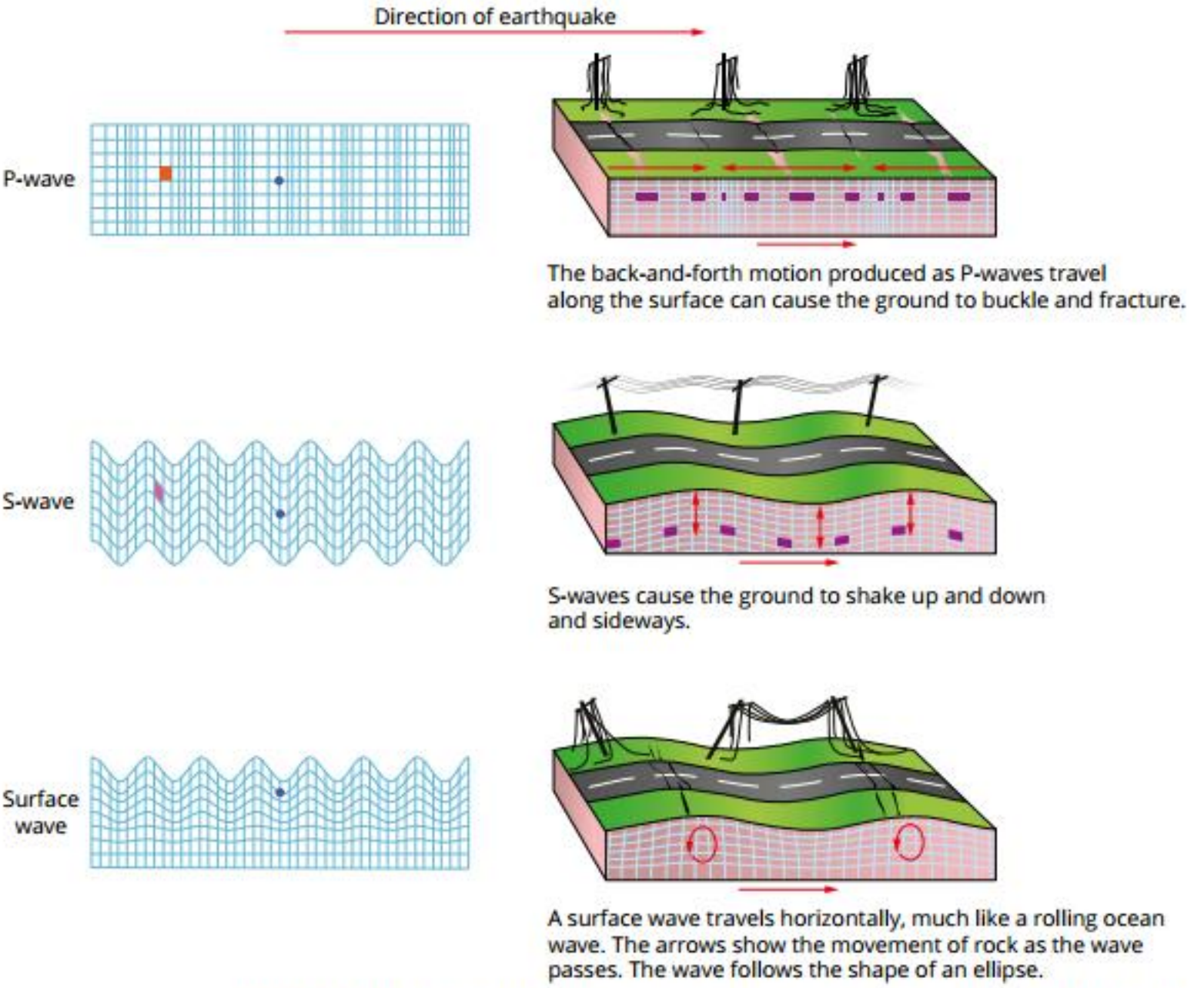

Direction of earthquake
P-wave
The back-and-forth motion produced as P-waves travel along the surface can cause the ground to buckle and fracture.
S-wave
S-waves cause the ground to shake up and down and sideways.
Surface wave
A surface wave travels horizontally, much like a rolling ocean wave. The arrows show the movement of rock as the wave passes. The wave follows the shape of an ellipse.

FIGURE 9.2.9 The three types of seismic waves, showing both wave type and effects on the Earth's crust

Worked example 9.2.3

SEISMIC WAVES

A longitudinal P-wave travelling at $3.0\,km\,s^{-1}$ is detected by a seismic station at 1.00.00 p.m. AEST. If the epicentre of the earthquake is 45 km away, determine the time at which the transverse S-wave is detected at the same seismic station. Assume the S-wave is travelling at half the speed of the P-wave.

Thinking	Working
Assume the S-wave has half the speed of the P-wave. Rearrange the speed equation $v = \frac{d}{t}$ to solve for time. $v = 1.5\,km\,s^{-1}$ $d = 45\,km$	S-wave: $t = \frac{d}{v}$ $= \frac{45}{1.5}$ $= 3.0 \times 10^{1}\,s$
S-waves arrive later as they are transverse seismic waves. Convert to standard time.	The time the S-waves are detected is 1.00.30 p.m.

➤ Try yourself 9.2.3

SEISMIC WAVES

The University of Queensland Seismology Station reported that seismic waves have been recorded at their seismic station in Saint Lucia. The longitudinal P-waves were travelling at 3.0 km s^{-1} and the transverse S-waves were travelling at 1.5 km s^{-1}. If the epicentre of the earthquake was 90.0 km away, and the earthquake happened at 7.35.00 a.m., calculate the times when the station detected the P-waves and the S-waves.

Stringed instruments

When a guitar string is plucked, the vibrating object produces a sound wave. Surrounding air molecules start to vibrate in unison with the guitar string, as shown in Figure 9.2.10. This air particle motion is in the same direction as the travelling sound wave. This is an example of a longitudinal wave. The wave on the guitar string is a transverse wave as the string vibrates, or oscillates, perpendicular to the direction of the travelling wave in the string, setting up a standing wave, which will be discussed later in Module 9.7.

The frequency of the vibrating air molecules is the same as the frequency of the vibrating guitar string. The speed of sound in air is 340 m s^{-1} at room temperature.

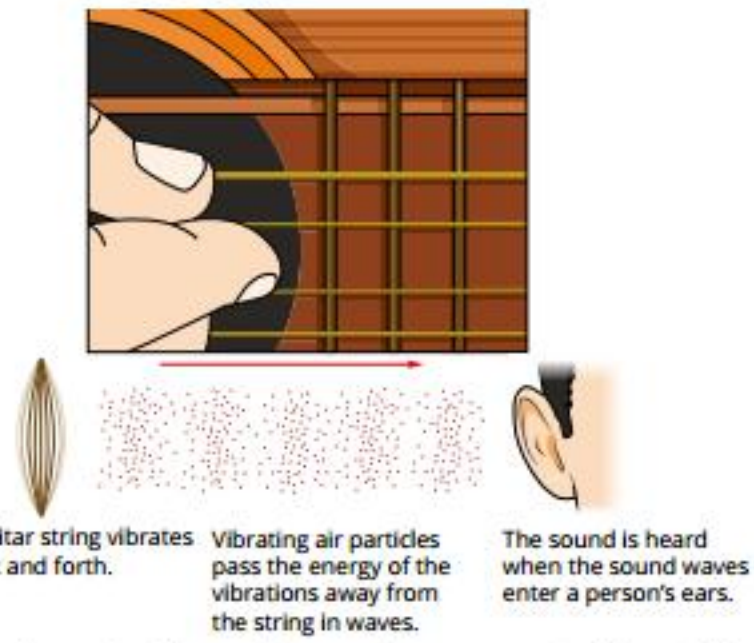

A guitar string vibrates back and forth.
Vibrating air particles pass the energy of the vibrations away from the string in waves.
The sound is heard when the sound waves enter a person's ears.

FIGURE 9.2.10 A vibrating guitar string and the resulting movement of air particles passing on the energy of the vibrations

Tsunami waves

An example of a transverse wave is a **tsunami** wave. The Earth's tectonic plates constantly move against each other, causing one plate to slip below another plate. This sudden giving way is felt as an earthquake as the tectonic plate boundary snaps back up. This displacement of the Earth's tectonic plate forces the water immediately above it to move up. This results in a massive displacement of water in the ocean. Deep-ocean tsunamis are barely noticed on the ocean surface but as the wave reaches land, the tsunami increases in height as the water becomes shallower, as shown in Figure 9.2.11. This wave phenomenon is also well known near sand banks, where navigation of boats needs to take this phenomenon into account, for example, when entering the ocean from a river inlet. Tsunami waves have been recorded as high as 30–40 metres in wave height near landfall.

All tsunami waves **dissipate** (or lose) energy as the wavefronts radiate outwards from the point of origin. As the waves travel outwards from the source, the energy is spread out over a greater volume of water. This has the effect of reducing the impact of the tsunami when it reaches land.

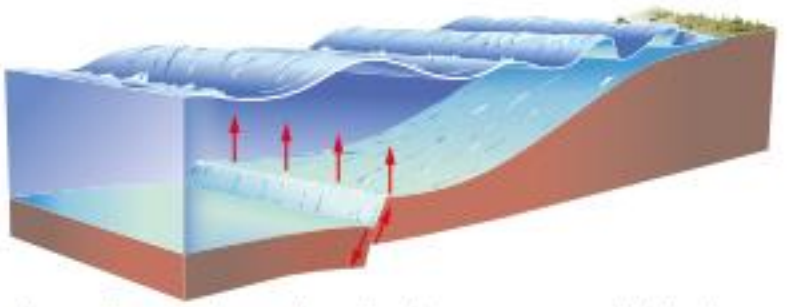


FIGURE 9.2.11 The tsunami wave shown above is a transverse wave in the deep-water section.

Some of the most devastating tsunamis ever recorded have happened in the twenty-first century.

- On 11 March 2011 a tsunami hit the nuclear power plant at Fukushima. It was triggered by a magnitude 8.9 earthquake off the east coast of northern Japan. The epicentre of the earthquake was approximately 130 km off the coast of Sendai.
- On 26 December 2004 (Boxing Day) a tsunami was triggered in the Indian Ocean when the Indo–Australian plate subducted (slipped) below the Eurasian plate. It was caused by an earthquake of magnitude greater than 9.0. The earthquake caused the seafloor to uplift, displacing the seawater above it. The impact zone of this tsunami is shown in Figure 9.2.12.

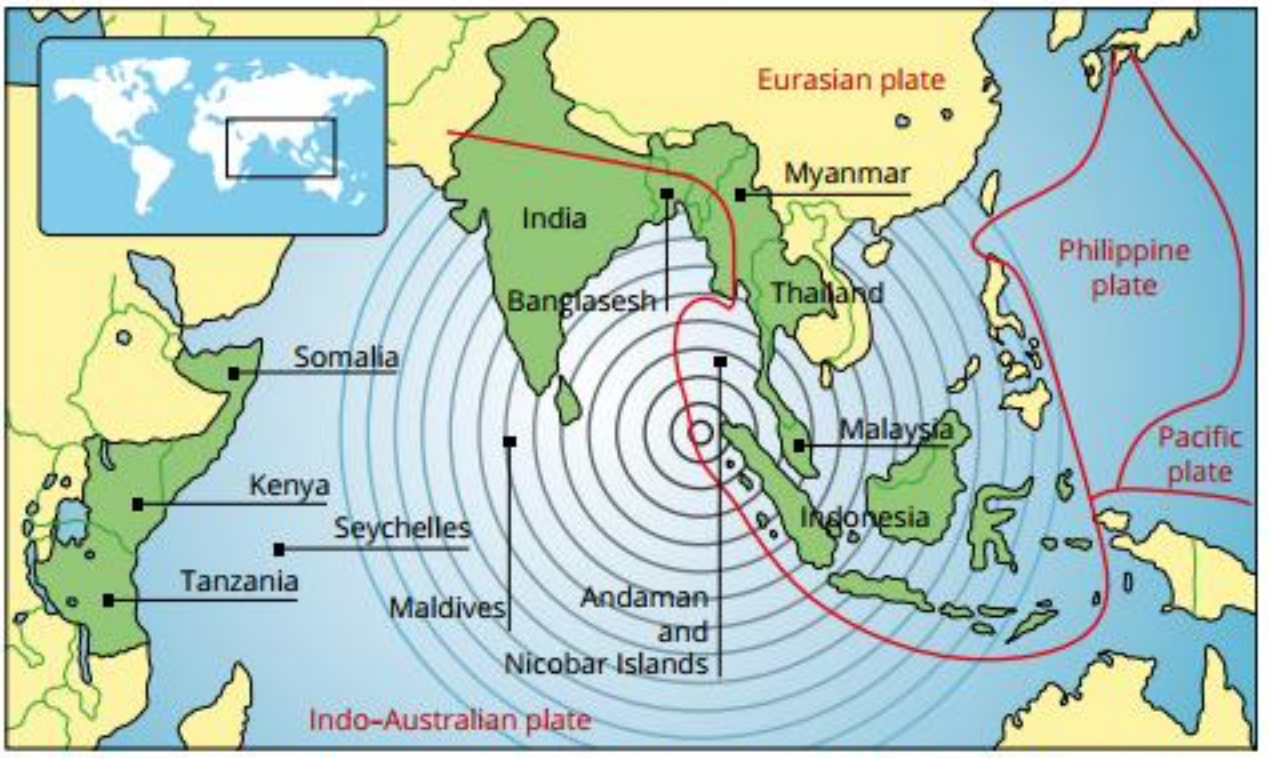


FIGURE 9.2.12 The map of the Indian Ocean tsunami shows the point of subduction between two massive plates at the centre of the concentric circles. Note the wavefronts (concentric circles) showing how the tsunami wave dissipated energy over distance.

9.2 Review

SUMMARY

- In a transverse wave, the oscillations are perpendicular to the direction in which the wave energy is travelling. Examples of transverse waves include waves in strings, seismic S-waves, and tsunami waves.
- In a longitudinal wave, the oscillations are parallel to the direction in which the wave is travelling. Examples of longitudinal waves include sound waves, and seismic P-waves.
- Both longitudinal and transverse waves can be represented by drawing wavefronts and rays. The distance between wavefronts is one wavelength, λ. The ray is drawn in the direction of net energy transfer.
- The wavelength of a longitudinal wave is the distance between successive compressions, or the distance between successive rarefactions.
- From graphs of longitudinal waves and transverse waves, you can determine the amplitude, period, frequency and wavelength.

KEY QUESTIONS

Describe

1 Identify whether statements a–d are true or false. Rewrite the false statements to make them true.

a Longitudinal waves occur when the particles vibrate perpendicular to the direction of energy transfer of the wave.

b Transverse waves occur when the particles vibrate parallel to the direction of energy transfer of the wave.

c In sound waves, the area of expansion is called a rarefaction.

d The vibrating string of a guitar is an example of a longitudinal wave.

2 Describe the motion of the particles in a seismic P-wave.

Apply

3 Classify the waves described below as either longitudinal or transverse waves:

a tsunami waves

b seismic P-waves

c seismic S-waves

d slinky moved backwards and forwards

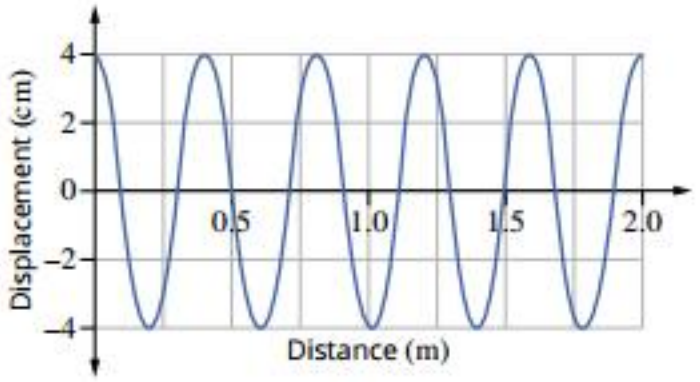
e air particles bunching up and stretching out due to changes in air pressure.

4 Draw a displacement–time graph and displacement–position graph for a transverse and a longitudinal wave. Explain the key attributes of each graph.

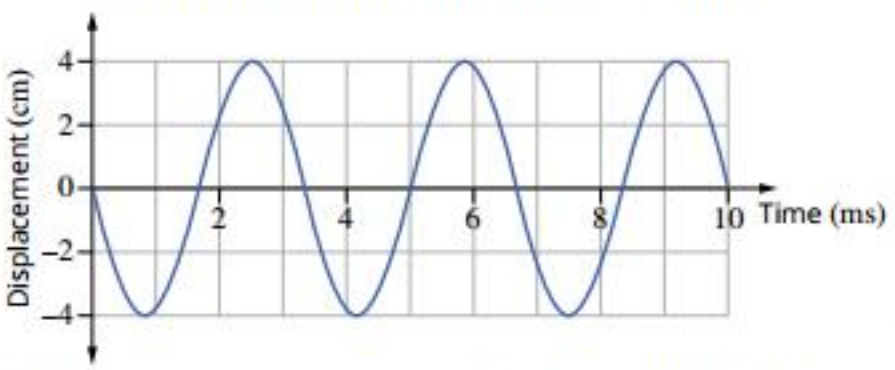
5 Seismic S-waves were detected 25 s after an earthquake. The waves were travelling at 3 km s^{-1}. How far from the epicentre was the detector in m?

Analyse

6 A displacement–distance graph of a longitudinal sound wave is shown below. Calculate the amplitude, A, and wavelength, λ, of the wave.



7 A displacement–time graph for a transverse wave in a vibrating string is shown below. Calculate the amplitude, period and frequency of the wave.



8 A tuning fork is oscillating with an amplitude of 10 mm and producing the musical note A with a frequency of 440 Hz. The sound waves travel through the air at 340 m s^{-1}.

a Calculate the wavelength of the sound waves.

b Draw a displacement–time graph for the sound wave including labels and values.

c State whether the sound wave produced is a transverse or longitudinal wave. Explain the air particle oscillations with reference to the graph drawn in part **b**.

9.3 Reflection

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall the conservation of energy of a wave at a change in medium
- define 'reflection'
- describe the reflection of a wave or pulse at a boundary between two media
- use a ray diagram to represent the path of a wavefront
- recall the law of reflection
- interpret ray diagrams, particularly angle of incidence, angle of reflection, the normal line and the mirror surface
- use the wave model of light and the law of reflection to explain the position of an image in a mirror
- recall that an image observed in a plane mirror undergoes horizontal reversal
- recall there is no change in frequency when a wave is reflected off a surface such as a mirror.

Mechanical waves transfer energy through a medium, in contrast to electromagnetic waves, which do not need a medium at all (this will be discussed further in Chapter 11 on light). A medium is necessary for the mechanical wave to transfer energy, but there will be times when that medium physically ends, such as when a water wave meets the edge of a pool or air meets a wall. A change in the physical characteristics in the same medium, such as density and temperature, can act like a change in medium. When the medium ends, or changes, the wave does not just stop. Instead, the energy that the wave is carrying will undergo three processes:

- some energy will be reflected (Figure 9.3.1)
- some energy will be absorbed by the new medium
- some energy will be **transmitted**.

The energy the wave is carrying is conserved regardless of how much is reflected, absorbed and transmitted.

Rarely in the real world does one mechanical wave occur in isolation. From the ripples that form on a pond hit by raindrops to the complex interactions of multiple reflected sound waves, the world is full of mechanical waves. The sounds produced by acoustic musical instruments and the human voice come from the interaction between sound waves and their **reflections**. The interaction of mechanical waves results in superposition and creates, among many other things, the characteristic sounds of musical instruments and of the human voice. This will be covered in more detail in Module 9.7.

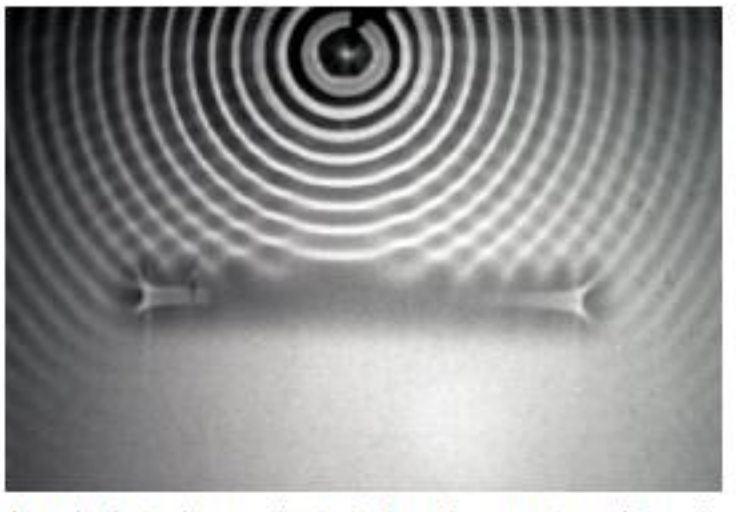


FIGURE 9.3.1 Waves in a ripple tank are reflected when they meet a solid surface. Here, a barrier positioned below the source of the circular waves reflects the waves.

When a transverse wave pulse reaches a hard surface, such as the fixed end of a rope, the wave is bounced back or reflected. When the end of the rope is fixed, the reflected pulse is inverted, as shown in Figure 9.3.2. A wave crest is reflected as a trough and a trough is reflected as a wave crest. The inversion of a reflected wave is a 180° **phase change**. The phase of a wave is described in fractions of wave cycles. One complete wave cycle or full period of a wave is expressed as 360°; half a wave cycle or half a period is expressed as 180°.

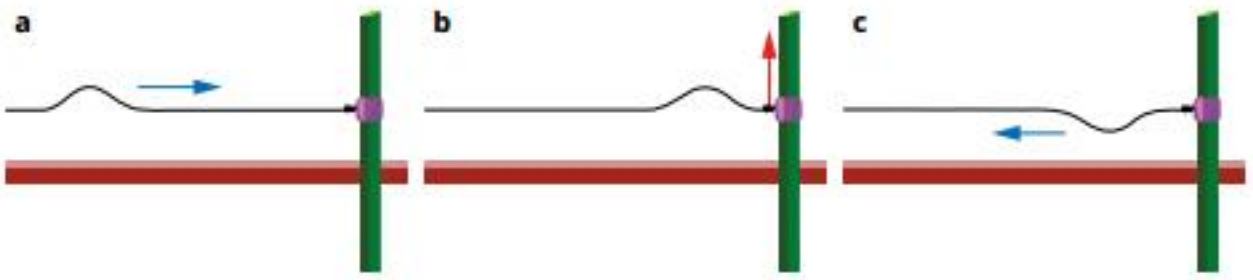


FIGURE 9.3.2 (a) A wave pulse moves along a string to the right and approaches a fixed end at the post. (b) When the wave reaches the post, the string exerts an upwards force on the fixed post. Due to Newton's third law, the fixed post exerts an equal and opposite force on the string, which inverts the wave pulse (c) and sends its reflection back to the left on the bottom side of the string. There is a phase reversal on reflection from the fixed end.

When a wave pulse hits the end of the rope that is free to move (known as a free boundary), the pulse returns with no phase change, as shown in Figure 9.3.3. The reflected pulse is the same as the incident pulse. A crest is reflected as a crest and a trough is reflected as a trough.

FIGURE 9.3.3 (a) A wave pulse moves along a string to the right and approaches a free end at the post. (b) When the wave reaches the post, the free end of the string is free to slide up the post. (c) No inversion happens and the wave pulse is reflected back to the left on the same side of the string; there is no phase reversal on reflection from a free end.

When the transverse wave pulse is reflected, the amplitude of the reflected wave is not quite the same as the original. Some of the energy of the wave is **absorbed** by the post and transformed into heat energy, and some of the energy will continue to travel through the post. You can see this more clearly by connecting a heavier rope to a lighter rope. The change in density has the same effect as a change in medium (Figure 9.3.4).

When a transverse wave pulse is sent down the rope from the light rope to the heavier rope, part of the wave pulse will be reflected and part of it will be transmitted to the heavier rope. As the second rope is heavier, a smaller proportion of the wave is transmitted into it and a larger proportion of the wave is reflected.

This is just the same as a wave pulse striking a wall. The more rigid and/or dense the wall, the more the wave energy will be reflected and the less it will be absorbed, but some energy will be absorbed by or transferred to the second medium. This explains why sound can travel through walls.

- When a transverse wave reaches a fixed end, the reflected pulse is inverted. A wave crest is reflected as a trough and a trough is reflected as a wave crest. The inversion of a reflected wave is a 180° phase change.
- When a transverse wave reaches a free boundary, the reflected pulse is not inverted and there is no phase change.
- When a transverse wave reaches a more rigid or heavier medium, some of the wave pulse is reflected and some is transmitted through the heavier medium. The reflected pulse will be inverted.

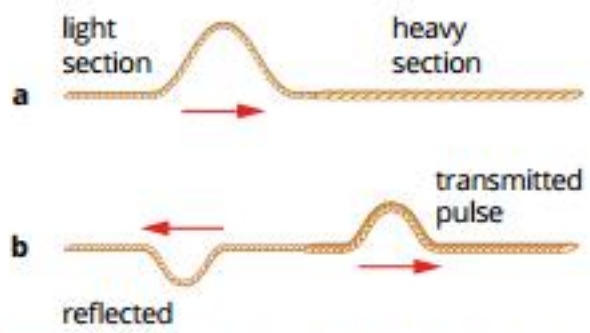


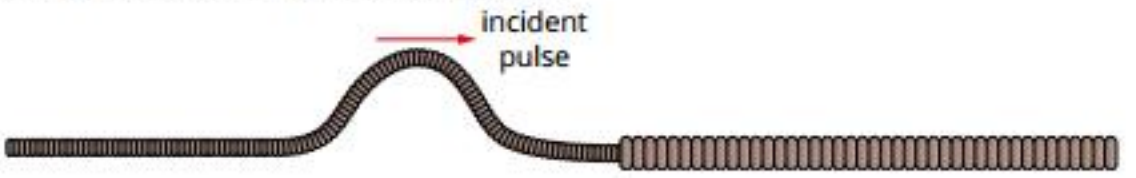
FIGURE 9.3.4 (a) A wave pulse travels along a light rope towards a heavier rope. (b) When the wave reaches a change in density, the wave pulse will be partly reflected and partly transmitted. This is analogous to a change in medium.

Worked example 9.3.1

REFLECTION

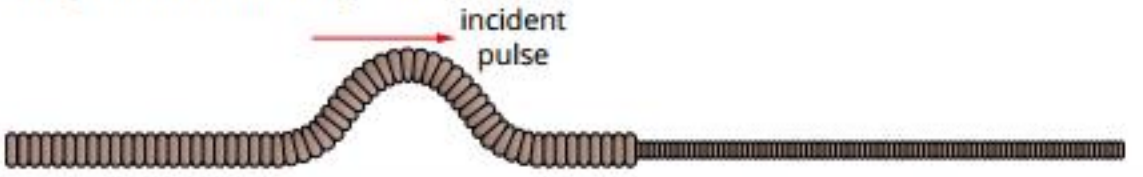
Predict what happens to the reflected pulse in each of the following situations using information about reflection.

a An incident transverse wave pulse travels to the right along a light string attached to a heavier string.



Thinking	Working
The incident pulse in the light string reflecting off the heavier string is like the pulse in a string being reflected from a fixed end. A pulse is also transmitted to the right into the heavier string.	The reflected pulse will be inverted.

b An incident transverse wave pulse travels to the right along a heavy string attached to a lighter string.



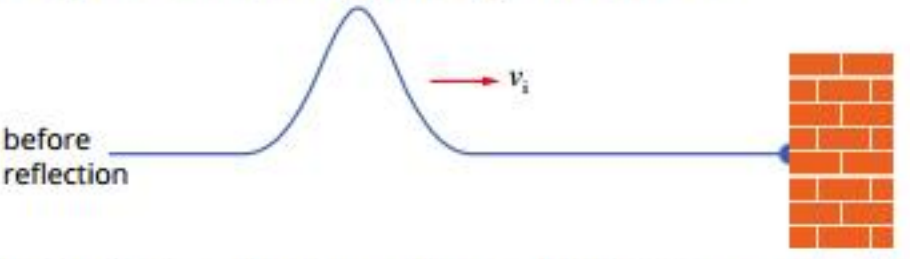
Thinking	Working
The incident pulse in the heavy string reflecting off the lighter string is similar to the pulse in a string reflected from a free end. A pulse is also transmitted to the right into the lighter string.	The reflected pulse will not be inverted. There is no change in phase.

➤ Try yourself 9.3.1

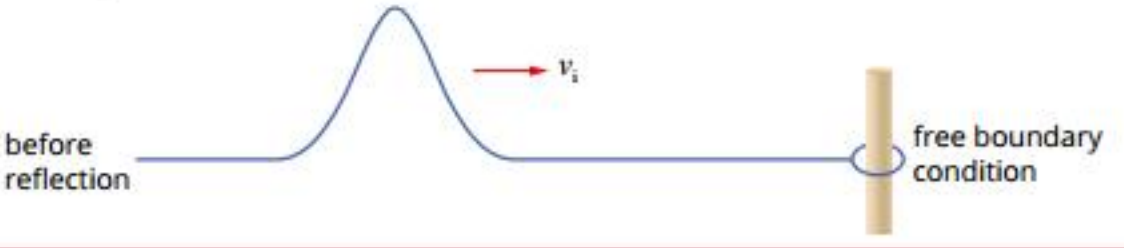
REFLECTION

Predict what happens to the reflected pulse in the string in each of the following situations, using the information about reflection.

a An incident pulse travels along a string fixed to a wall.



b An incident pulse travels along a string attached to a moveable hoop over a pole.



Reflected wavefronts

As introduced in Module 9.2, both two-and three-dimensional waves travel as wavefronts. When drawing wavefronts, it is common to show the crests of the waves, as shown in Figure 9.3.5. When close to the source, wavefronts can show considerable curvature and are spherical when generated in three dimensions. Where a wave has travelled a long distance from its source, the wavefront is nearly straight and is called a **plane wave** (Figure 9.3.5b). Plane waves can also be generated by a long, flat source, such as those often used in a ripple tank.

The direction of motion of any wavefront can be represented by a line drawn perpendicular to the wavefront and in the direction the wave is moving (Figure 9.3.5a). This is called a ray. Rays can be used to study or illustrate the properties of two- and three-dimensional waves without the need to draw individual wavefronts.

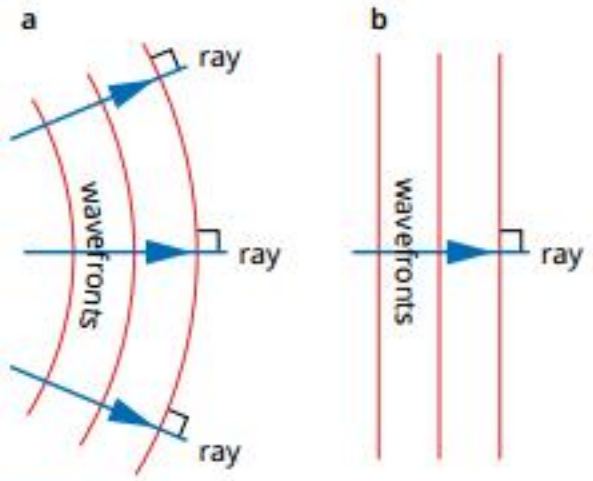


FIGURE 9.3.5 Rays can be used to illustrate the direction of motion of a wave. They are drawn perpendicular to the wavefront of a two- or three-dimensional wave and in the direction of travel of the wave; (a) illustrates rays for circular waves near a point source and (b) shows a ray for plane waves.

Ray diagrams can be used to illustrate the path of a wavefront reflecting from a surface. The incident and reflected waves are also shown. The **normal** in a ray diagram is an imaginary line at 90° to the reflecting surface, that is, perpendicular to the surface. For two- and three-dimensional waves, the angle between the normal and the incident waves is equal to the angle between the normal and the reflected waves.

The angles of the incident and reflected waves from the normal are labelled θ_i and θ_r respectively (Figure 9.3.6).

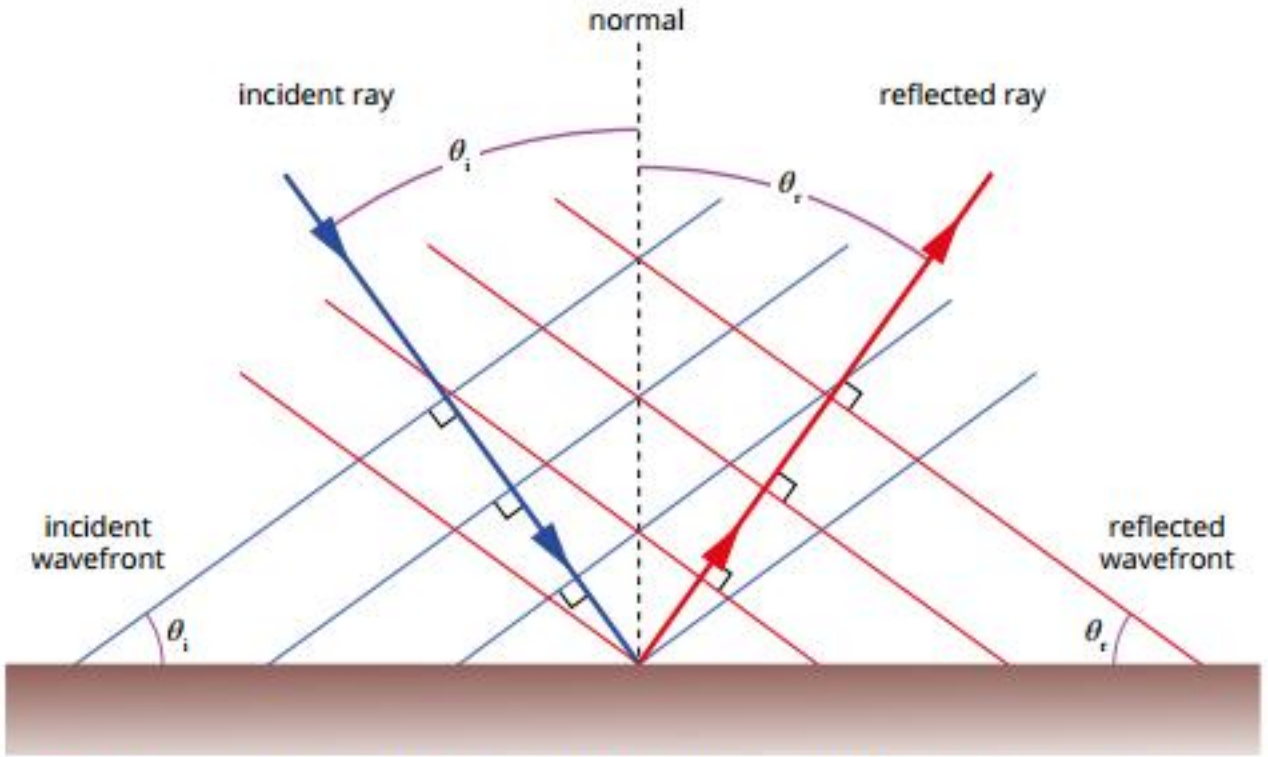


FIGURE 9.3.6 The law of reflection. The angle between the incident ray and the normal (θ_i) is the same as the angle between the normal and the reflected ray (θ_r).

This is referred to as the **law of reflection**. The law of reflection states that the **angle of reflection**, measured from the normal, equals the **angle of incidence** measured from the normal, that is $\theta_i = \theta_r$.

The law of reflection is true for any straight, curved or irregular surface. For all surfaces, the normal is drawn perpendicular to the surface at the point of contact of the incident wave.

When wavefronts meet an irregular, rough surface, the resulting reflection can be spread over a broad area. This is because each point on the surface may reflect the portion of the wavefront reaching it in a different direction, as seen in Figure 9.3.7. This is referred to as **diffuse reflection**.

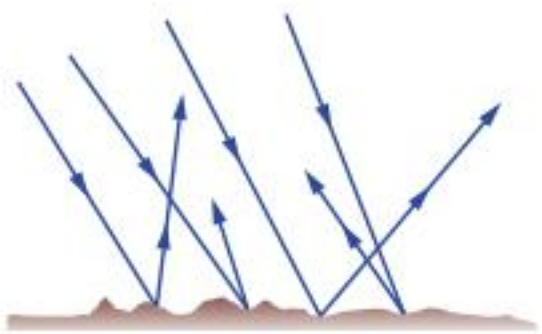


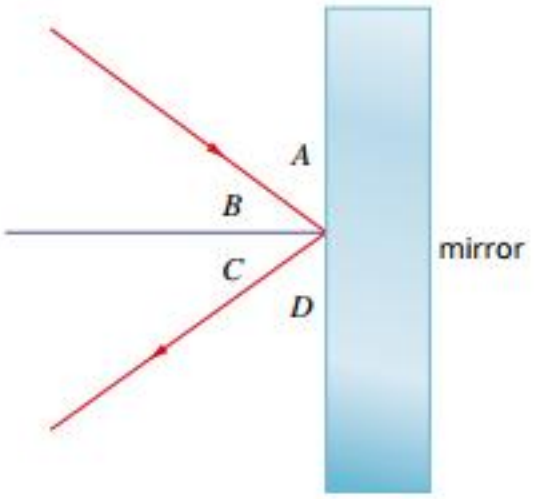
FIGURE 9.3.7 Reflection from an irregular surface. Each incident ray may be reflected in a different direction, depending upon how rough or irregular the reflecting surface is. The resulting wave will be diffuse (spread out).

Worked example 9.3.2

REFLECTED WAVEFRONTS

A light ray is incident on a flat surface mirror and reflects off the surface of the mirror as shown. Four labels *A*, *B*, *C*, and *D* have been drawn to represent the angles.

State the letters that represent the angle of the incident ray relative to the surface of the mirror, the angle of incidence, θ_i, and the angle of reflection, θ_r. Name the line that represents the imaginary normal line.



Thinking	Working
The angle between the incoming (incident) ray and the flat-surfaced mirror is the angle the ray strikes the mirror. The angle of incidence is the angle between the incident ray and the normal line, not the surface of the mirror. The angle of reflection is the angle between the reflected ray and the normal line. The normal line is a perpendicular line to the surface of the flat mirror. It is drawn at the point where the incident ray strikes the mirrors surface.	The angle the incident ray strikes the mirror at is the angle *A*. The angle of incidence, θ_i is represented by the letter *B*. The angle of reflection θ_r is represented by the letter *C*. The normal line is the flat horizontal line between *B* and *C*.

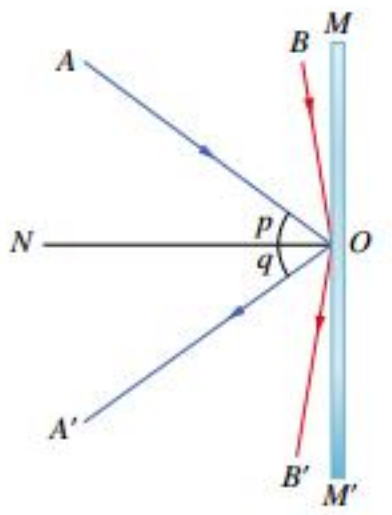
➤ Try yourself 9.3.2

REFLECTED WAVEFRONTS

Rays *A* and *B* are incident on a straight reflecting mirror surface, as shown below. The imaginary normal line has been drawn and labelled.

State the letters that represent the angle of incidence, θ_i, and the angle of reflection, θ_r, for ray *A* and ray *A*′. State the relationship between these angles. Name the line that represents the imaginary normal line.

For ray *B*, use the law of reflection to state the relationship between angles *BON* and *B*′*ON*.



Images in plane mirrors

The most obvious examples of reflection occur at the boundaries of plane mirrors. When you brush your teeth and look into a mirror, you observe the reflected **image** of yourself and your teeth, but the image is reversed. If you raise your right arm, you observe the left arm of the image being raised. If you hold up the toothpaste tube, the lettering will be reversed. This observation is referred to as horizontal reversal of an image.

When standing in front of a mirror, the reflected image appears to be the same distance behind the mirror as the object is in front of the mirror. The reflection is called an image because the light seems to converge on a point that is not real, because it is behind the mirror.

In Figure 9.3.8, two rays of light are travelling away from an **object**, O, and being reflected respectively at positions A and C at the mirror boundary. The reflected rays AB and CD travel towards the observer's eye. The rays appear to travel from position I, the image location. The distance the image appears from the surface boundary is the same as the distance from the object O to the surface boundary.

When you stand in front of a mirror, your image appears at the same depth, or distance behind the mirror, as you stand in front of the mirror. This is due to the law of reflection of the light rays off the surface of a plane boundary such as a flat mirror, shown in Figure 9.3.9.

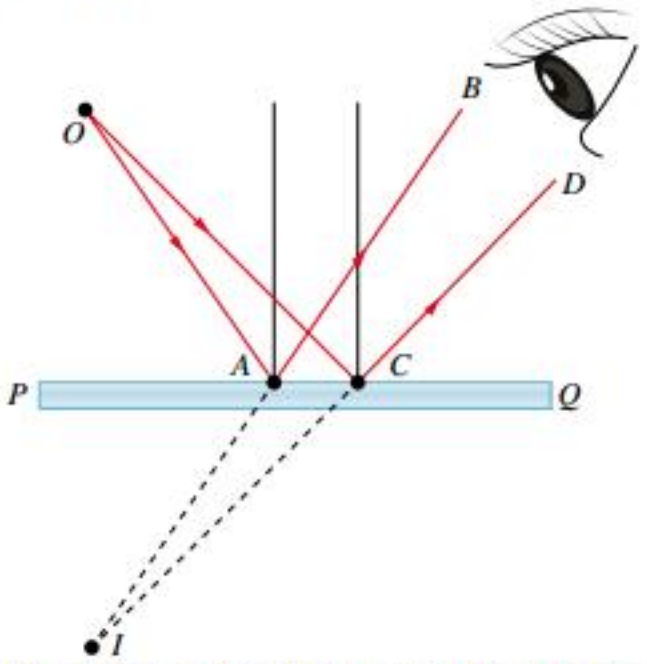


FIGURE 9.3.8 The rays OA and OC are incident on a flat mirror boundary and are reflected as respective rays AB and CD towards the observer. The dashed lines show the position of the observed image.

Try moving away from the mirror and notice the image moving away also.

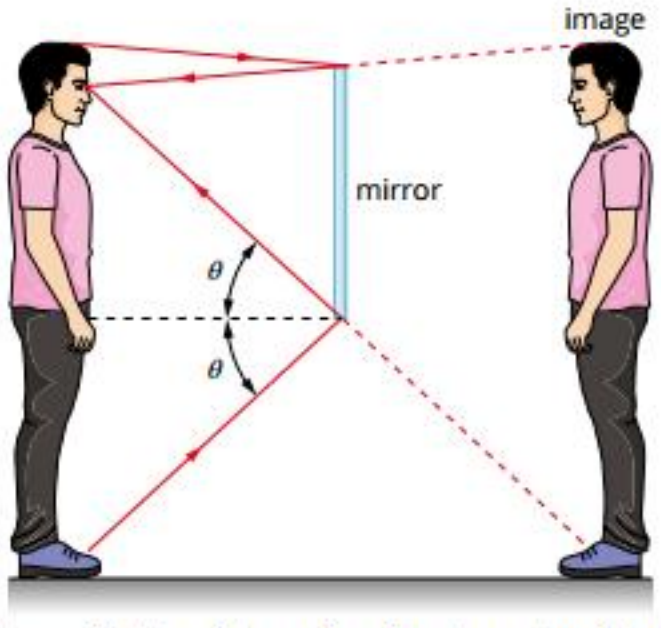


FIGURE 9.3.9 Two light rays reflecting off the surface of a plane mirror. The depth of the image from the mirror is identical to the depth of the person or object from the mirror.

Worked example 9.3.3

IMAGES IN PLANE MIRRORS

When you look in a mirror, where does the reflection appear? Select the most correct response and give a brief explanation.

A on the mirror

B in front of the mirror

C behind the mirror

D in the mirror

Thinking	Working
Incident light is reflecting off the surface of the mirror. The reflected light travels to the observer's eye. The reflected light ray appears to come from behind the mirror.	Correct answer is C – your reflection appears behind the mirror.
The explanation needs to be clear and concise.	Light rays reflect off the surface of the mirror at the same angle as the incident rays strike the surface. These reflected rays appear to originate from the image at the same distance behind the mirror.

➤ Try yourself 9.3.3

IMAGES IN PLANE MIRRORS

A person stands in front of a mirror and then takes a step closer to the mirror. What would the reflection appear to do? Select the most correct response and give a brief explanation.

A move closer to the mirror

B not move at all

C move away from the mirror

D stay in the mirror

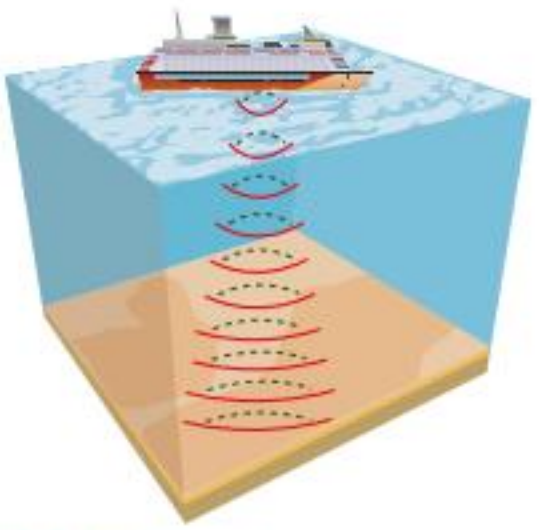


FIGURE 9.3.10 The ship sends a sound wave into the water below the ship. By measuring the time between the emitted sound (red waves) and its reflection (dashed lines), the ship's sonar can determine the depth of the water under the ship.

FIGURE 9.3.11 Sonar image of a shipwreck of a sunken lightship

Sonar images

Echoes provide the most obvious evidence that sound waves are reflected. Like all waves, sound can be reflected when it strikes an obstacle, or there is a change in the medium.

The phenomenon of an echo can be used to measure extremely large distances. For example, an echo-sounding device is used to measure the depth of the sea (Figure 9.3.10). This equipment works by measuring the time taken for the echo of a sound wave to be reflected by the seabed back to a ship. Another use of echo-sounding devices is to produce images of shipwrecks on the seabed floor, as is shown with the image of a sunken lightship in Figure 9.3.11.

Worked example 9.3.4

SONAR IMAGES

The Mariana Trench is a very deep-sea trench located in the western Pacific Ocean near the Philippines. It has a maximum known depth of 10994 m below the surface of the ocean.

Sound waves travel 4.3 times faster in water than air. The speed of sound in water is 1481 $m s^{-1}$ when the temperature of the water is 20°C. Calculate the time taken for the echo signal generated by a ship to travel to the bottom of the trench and return to the ship.

Thinking	Working
Assume the speed of sound in the water is 1481 $m s^{-1}$. The total distance travelled by the echo is twice the ocean depth. $d = 21988\,m$ Rearrange the equation for velocity to solve for time: $t = \frac{d}{v}$	Time t for echo signal to return to the ship: $t = \frac{d}{v}$ $= \frac{21988}{1481}$ $= 14.85\,s$

➤ Try yourself 9.3.4

SONAR IMAGES

Many species of bats use sonar and echolocation to avoid obstacles during flight, forage for food and to locate their roosts. The echolocation calls of bats range in frequency from 20 to 80 kHz. This is beyond the range of human hearing and commonly referred to as ultrasonic.

A bat emits an ultrasound call and receives the return echo from its prey some 0.25 s later. Calculate how far away the bat is from its prey if the speed of sound in air is 340 $m s^{-1}$.

9.3 Review

SUMMARY

- A wave reaching the boundary between two materials in which it can travel will always be partly reflected, partly transmitted and partly absorbed because of the law of conservation of energy.
- A wave has been reflected if it bounces back after reaching a boundary or surface.
- Waves reflect with a 180° phase change from fixed boundaries. That is, crests reflect as troughs and troughs reflect as crests.
- Waves reflect with no phase change from free boundaries. That is, crests reflect as crests and troughs as troughs.
- When a wave is reflected from a surface, the angle of reflection will equal the angle of incidence.
- The image of an object will appear behind the surface of the mirror. There is no change in frequency when a wave is reflected off a surface such as a mirror.
- An image observed in a vertical plane mirror appears to undergo horizontal reversal.

KEY QUESTIONS

Describe

1 A wave travels along a rope that is fixed to a wall. Recall what happens after the wave reaches this fixed end.

2 A pulse is travelling along a string to a free end. Explain what happens to the pulse once it reaches the free end. Consider the amplitude and the pulse orientation.

3 Recall what happens to the energy of a pulse when it reaches a boundary between two different media.

Apply

4 Identify which of the following properties of a wave can change when the wave is reflected: frequency or amplitude.

5 A light ray strikes a flat mirror surface at an angle of 38° to the mirror. Determine the angle of reflection of the ray.

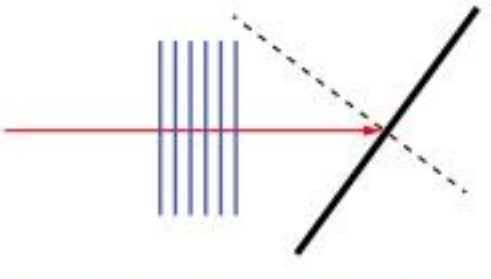
6 Explain how the inverted or upside-down image of the mountain on a flat lake surface is formed when viewed from above the surface of the lake, as seen in the photo. Hint: you may need to use a ray diagram in the explanation.

7 A submarine is travelling in cold water 45.0 m from the bottom of the ocean in that area. A sonar echo (directed to the bottom of the ocean) is received 0.031 s after the original signal was sent. Calculate the speed of sound in the cold seawater.

Analyse

8 Write how the word Physics would appear in a plane mirror.

9 Plane waves are incident on a boundary between two media, as shown in the diagram. Construct the reflected ray and six reflected wavefronts for the incident ray shown. Label the angle of incidence and the angle of reflection.



9.4 Refraction

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define 'refraction'
- describe the refraction of a wave at a boundary between two media
- explain the property of refraction using the wave model of light
- state the theoretical basis for explaining wave propagation (Huygens' principle)
- interpret ray diagrams for waves speeding up or slowing down when light waves travel from one medium to another
- recall how frequency, speed and wavelength of light waves are affected by various types of media
- use the principle of refraction to explain the apparent position of objects that are under water, and the shape of the Sun at sunrise and sunset
- provide examples of when refraction occurs for types of waves other than light waves.

In Module 9.3, you learnt that waves are reflected when they meet a solid surface, and explored how an image is reflected in a mirror using the wave model of light. In this module, you will learn about another property of waves: refraction.

Refraction of light can be seen when a straw sits in a glass of water and appears to bend at the boundary of the air and water (Figure 9.4.1). Other examples of refraction include the oval shape of a setting or rising sun, and when spear fishermen are hunting for fish below the water's edge. Refraction describes the change in direction of waves as they travel from one medium to another; for example, as light travels from air into water. Refraction is most commonly observed for light, but it also occurs for other types of waves, such as water waves, seismic waves and sound. In this module, you will study the refraction of light, and see that refraction also occurs in seismic waves and sound waves.

FIGURE 9.4.1 The straw in the glass appears to have a bend. This apparent bend is due to refraction of light.

HUYGENS' PRINCIPLE

In Module 9.2, you learnt how to draw wavefronts and rays to illustrate the direction of motion of a wave. The theoretical basis for wave **propagation** in two dimensions was first explained by the Dutch scientist Christiaan Huygens in 1678. **Huygens' principle** states that each point on a wavefront can be considered as a source of secondary wavelets (small waves).

Consider the plane wave shown in Figure 9.4.2. Each point on the initial wavefront can be treated as if it is a point source producing circular waves, some of which are shown in green. After one period, these circular waves will have advanced

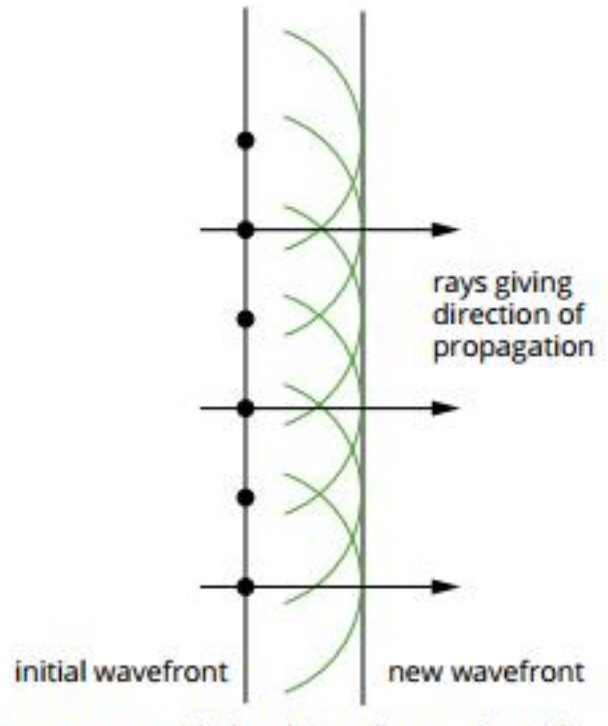


FIGURE 9.4.2 Each point on the wavefront of a plane wave can be considered as a source of secondary wavelets. These wavelets combine to produce a new plane wavefront.

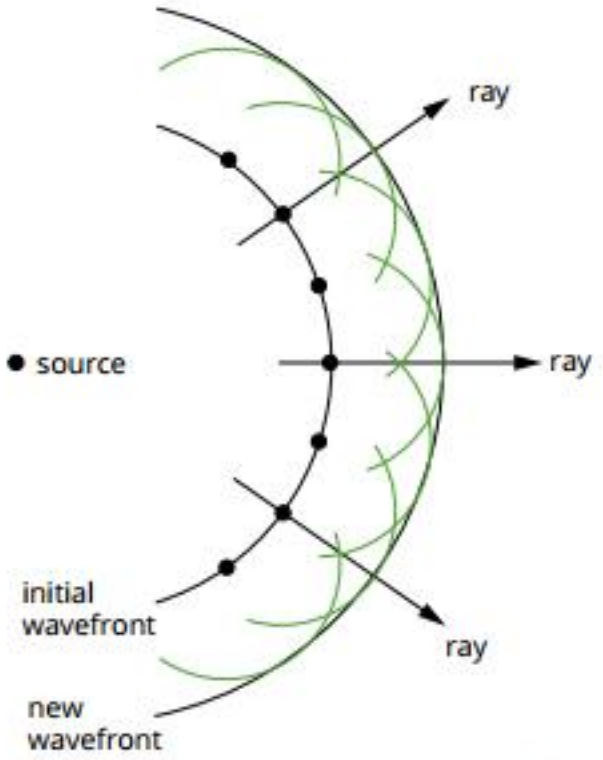


FIGURE 9.4.3 Each point on the wavefront of a circular wave can be considered as a source of secondary wavelets. These wavelets combine to produce a new circular wavefront.

by a distance equal to one wavelength. Huygens proved mathematically that when the amplitudes of each of the individual circular waves are added, the result is another plane wave as shown by the new wavefront.

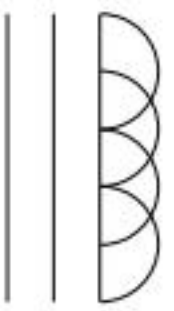
This process is repeated at the new wavefront, causing the wave to propagate in the direction shown. Circular waves are propagated in a similar way, as shown in Figure 9.4.3.

Huygens' principle is useful for understanding wave behaviour, including refraction.

Worked example 9.4.1

APPLYING HUYGENS' PRINCIPLE

On the plane wave shown moving from left to right below, sketch some of the secondary wavelets on the wavefront and draw the appearance of the new wavefront formed after one period.

Thinking	Working
Sketch several secondary wavelets on the advancing wavefront. Each secondary wavelet has the same radius as it propagates outward with equal speed. During one period the amplitudes of the secondary wavelets add up to produce a new wavefront that has progressed in the direction of the energy transfer of the wave.	
Sketch the new wavefront that is a combination of the secondary wavelets.	

➤ Try yourself 9.4.1

APPLYING HUYGENS' PRINCIPLE

On the circular waves shown below, sketch some of the secondary wavelets on the outer wavefront and draw the appearance of the new wavefront formed after one period.

REFRACTION OF LIGHT

Refraction is a change in the direction of light caused by changes in its speed. Changes in the speed of light occur when light passes from one medium (substance) into another. For example, the speed of light in air, or a vacuum, is approximately 300 000 km s^{-1} but in normal glass the speed of light is approximately 200 000 km s^{-1}.

In Figure 9.4.4, the light changes direction as it leaves the glass prism and re-enters the air.

FIGURE 9.4.4 Light refracts as it moves from one medium (the semicircular glass prism) into another (air) causing a change in direction.

In Figure 9.4.5, light waves move from an incident medium, where they have high speed, v_1, into a transmitting medium, where they have a lower speed, v_2. While the wave travels a distance $v_1\Delta t$ from B to D in the incident medium, it travels a shorter distance $v_2\Delta t$ from A to C in the transmitting medium. To do this, the wavefronts must change direction or 'refract' as shown.

Light waves behave in a similar way when they move from a medium such as air into water. The direction of the refraction depends on whether the waves speed up or slow down when they move into the new medium. The angle of incidence, i, is the angle between the direction of propagation and the normal and the angle of refraction, r, is the angle between the direction of reflection and the normal.

In Figure 9.4.6, light waves slow down as they move from air into glass, so the direction of propagation of the wave is refracted towards the normal. The angle of incidence, i, is greater than the angle of refraction, r.

In Figure 9.4.7, light waves speed up as they move from glass into air, so the direction of propagation of the wave is refracted away from the normal. The angle of incidence, i, is less than the angle of refraction, r.

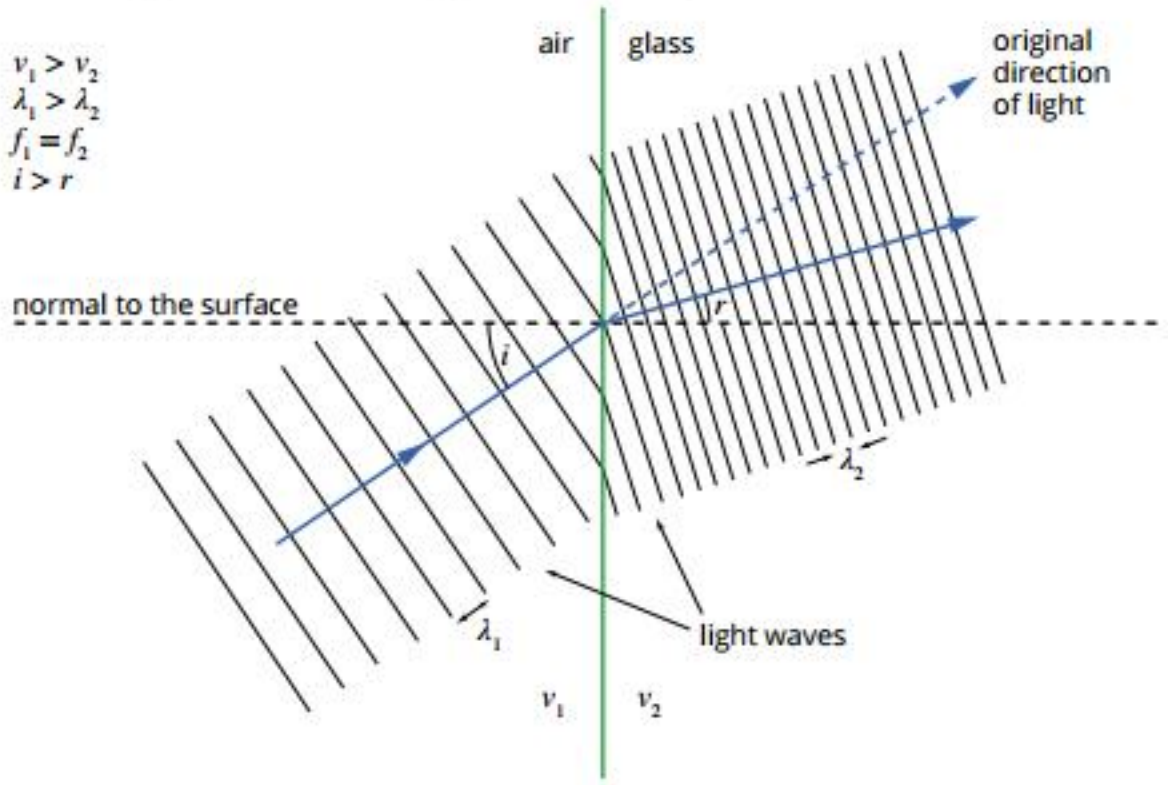


FIGURE 9.4.6 Light waves refract towards the normal when they slow down.

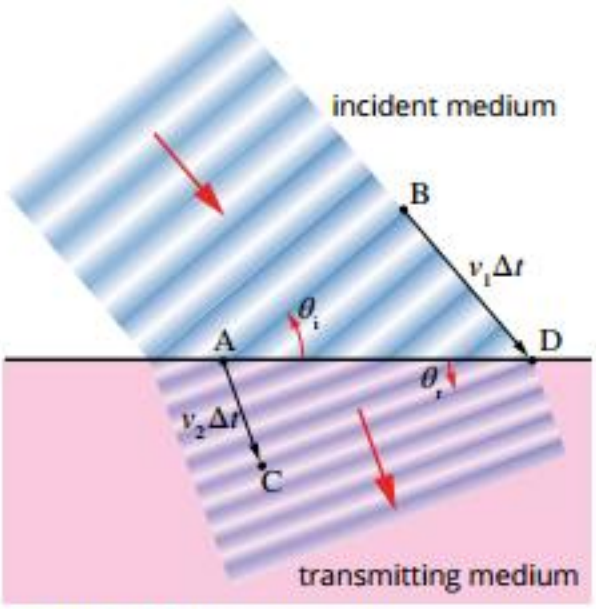


FIGURE 9.4.5 Wave refraction occurs because the distance A to C travelled by the wave in the transmitting medium is shorter than the distance B to D that it travels at the same time in the incident medium.

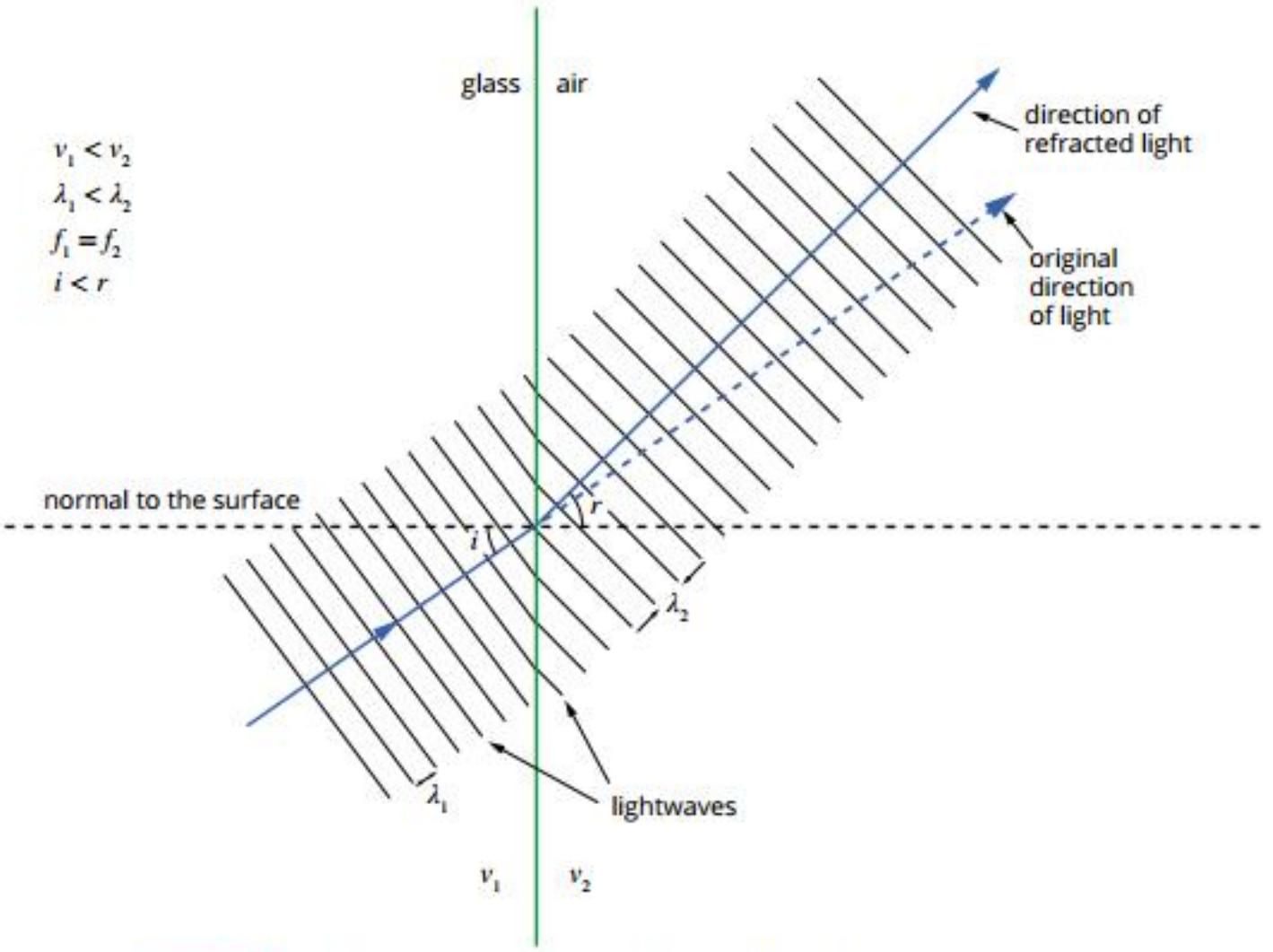


FIGURE 9.4.7 Light waves refract away from the normal when they speed up.

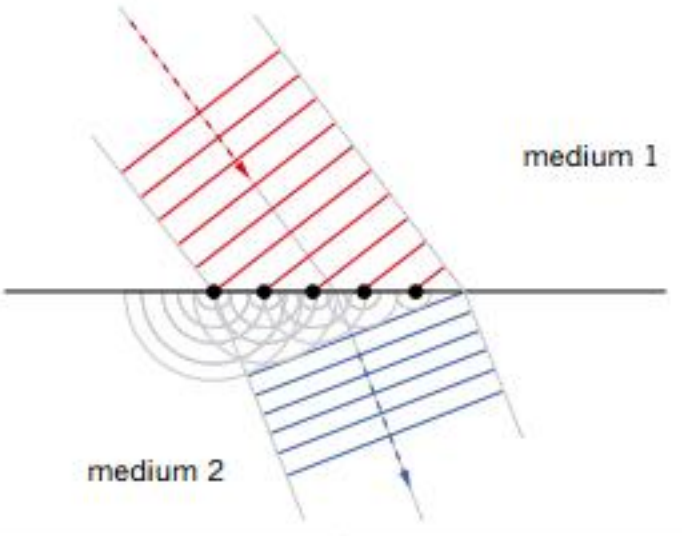
When light crosses the boundary of two media, the speed and wavelength of the wave changes in the same ratio. For example, when light travels from air into glass, the light wave slows down and the crests and troughs bunch up at a boundary, so the same number of wavefronts pass per second.

This can be illustrated using the wave equation: $f = \frac{v}{\lambda}$. If the speed and the wavelength change in the same ratio, then these factors will cancel and the frequency will not change.

Worked example 9.4.2

REFRACTION OF LIGHT

Wavefronts travel through medium 1, as shown in the diagram below. The wavefronts refract (or bend) at the boundary between the two media and continue to travel through medium 2.



a State in which medium the waves are travelling faster.	
Thinking	**Working**
The wavefronts are further apart in medium 1 than in medium 2. If the frequency does not change, then the speed of the wave is dependent on the wavelength only (due to the wave equation). The distance between the wavefronts corresponds to the wavelength of a wave.	The waves are travelling faster in medium 1.
b State your observations in terms of comparing the angle of incidence and the angle of refraction.	
Thinking	**Working**
The angle of incidence, θ_i, is the angle measured between the normal line and the incident ray. The angle of refraction, θ_r, is the angle between the refracted ray and the normal line. The normal line, which is not evident in this diagram, is an imaginary line drawn perpendicular to the boundary at the point where the ray meets the boundary.	The angle of incidence is greater than the angle of refraction. The refracted ray bends towards the normal line.
c Explain your answer to the first part of the question using Huygens' principle.	
Thinking	**Working**
Applying Huygens' principle to explain your answer.	As each part of the incident wavefront in the top medium moves into the bottom medium, the distance travelled in the same time interval is less. This can be shown by the five dots, each representing a particle on the wavefront. Each secondary wavelet travels a shorter distance in medium 2 in one period. The wavefronts are closer together, indicating the speed of the wave is less (as the frequency remains unchanged).

➤ Try yourself 9.4.2

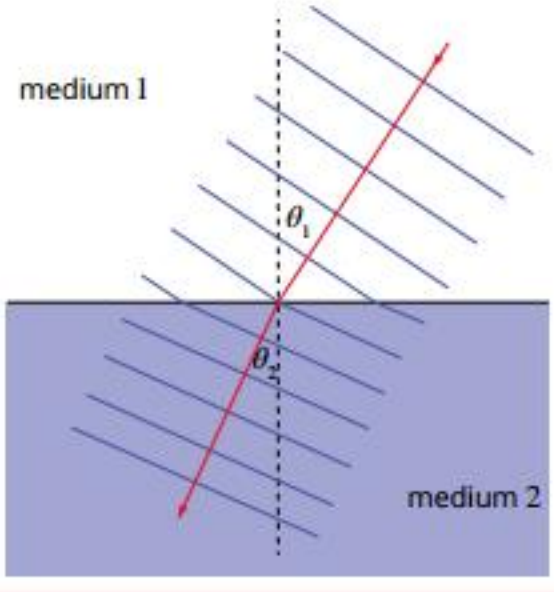
REFRACTION OF LIGHT

The labelled diagram below shows wavefronts travelling through two different media. Note the solid horizontal boundary line between the two media.

a State the medium in which the waves are travelling faster.

b State your observation in terms of comparing the angle of incidence and the angle of refraction

c Explain your answer to part (a) using Huygens' principle.



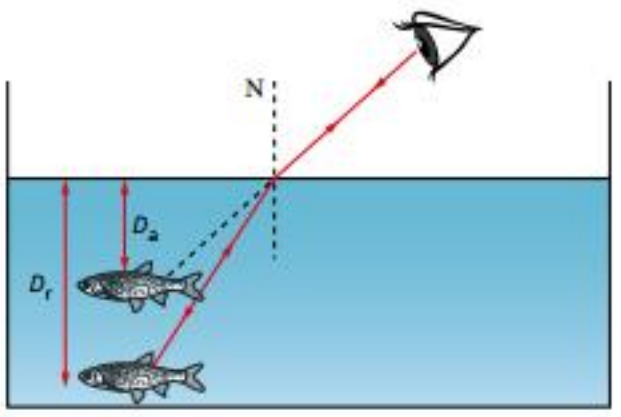


FIGURE 9.4.8 The apparent depth D_a of a fish compared to the real depth D_r as seen from above the air-water boundary

FIGURE 9.4.9 The shape of the Sun appears flatter as it approaches the horizon. It looks less circular and more oval-shaped.

Apparent position of objects under water

Indigenous fishermen using spears know that when they see a fish in the water, the **real position** of the fish is not where they see the fish. They have learnt to aim a little lower than where they see the fish, or they may have a spear that has several spears evenly spread along the shaft, which increases the probability of striking a fish at its **real depth**.

The **apparent depth**, D_a, and the real depth, D_r, of the fish is shown in Figure 9.4.8. This difference between real depth and apparent depth is due to the refraction of the light rays travelling up from the fish through the water to the water–air boundary, and into the air above to the observer. The change in medium results in a change in velocity of the light waves; the light waves speed up in air, making the light ray bend, or refract, at the water–air boundary. In this case, the light ray speeds up and bends away from the imaginary normal line (N). Therefore, the light rays are refracted at the water–air boundary before they enter the observer's eyes. So, the fish appears at the apparent depth D_a and not the real depth D_r.

Sun shape at sunrise and sunset

When the Sun is near the horizon during sunset, it appears to be more oval-shaped than circular, as shown in Figure 9.4.9. Notice how the shape of the Sun appears to distort as it approaches the horizon.

During sunrise and sunset, light rays from the Sun travel a further distance through the atmosphere than at midday, when the Sun is directly overhead. The atmosphere consists of layers due to the air thinning with increasing altitude. This layered atmosphere structure continuously refracts the light rays until they reach the observer's eye. Refraction of light by these layers makes the Sun appear flattened or distorted.

At sunset and sunrise, the lower part of the Sun is closer to the horizon and is refracted more than the top part of the Sun (Figure 9.4.10). The observed effect is that the bottom of the Sun is lifted more than the top. The Sun appears more oval. The circular Sun is the object and the flatter, oval Sun is the image seen by the observer. The length of a day appears to be about 4 minutes longer than it is due to refraction of sunlight.

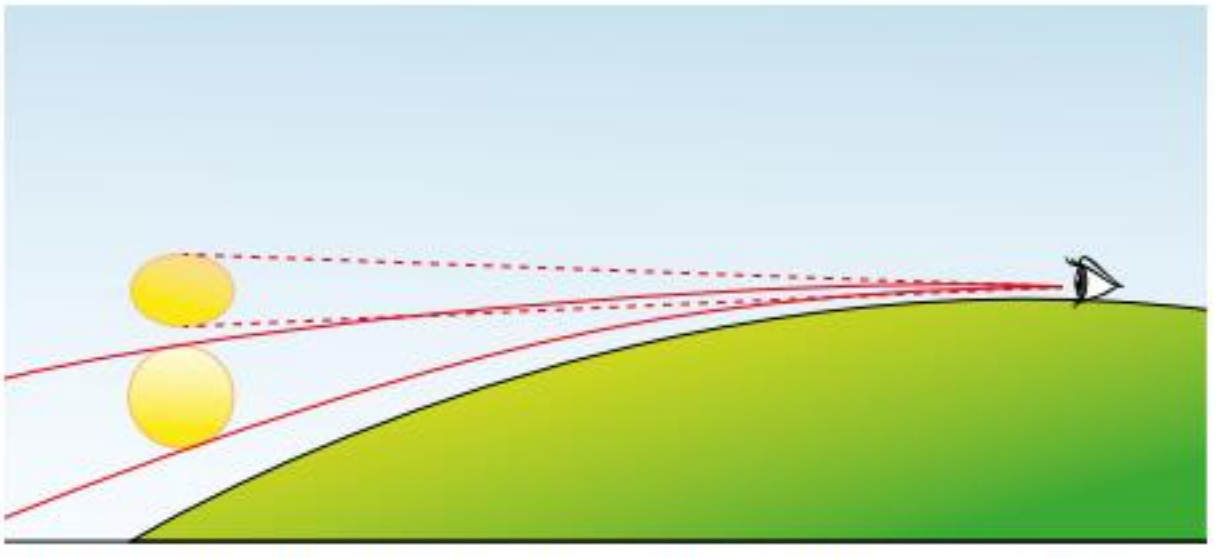


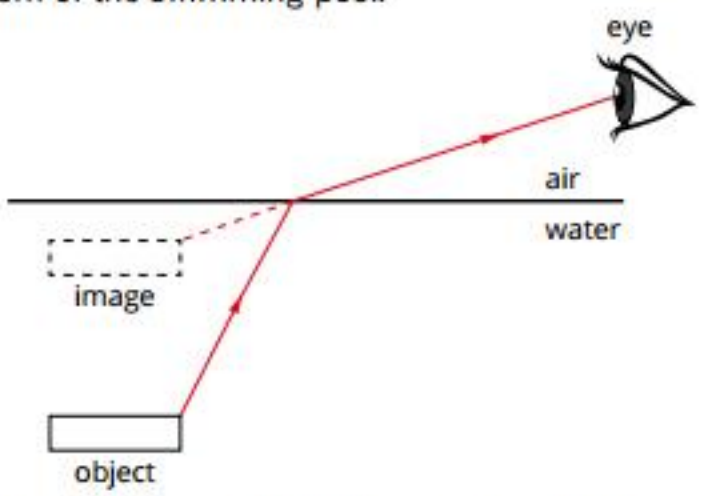
FIGURE 9.4.10 The actual position of the Sun (circular Sun) and the image seen (the flatter Sun)

Worked example 9.4.3

REFRACTION OF LIGHT AND APPARENT POSITION

When standing on the edge of a swimming pool and looking downwards into the water, is the apparent depth of the swimming pool deeper or shallower than its true depth?

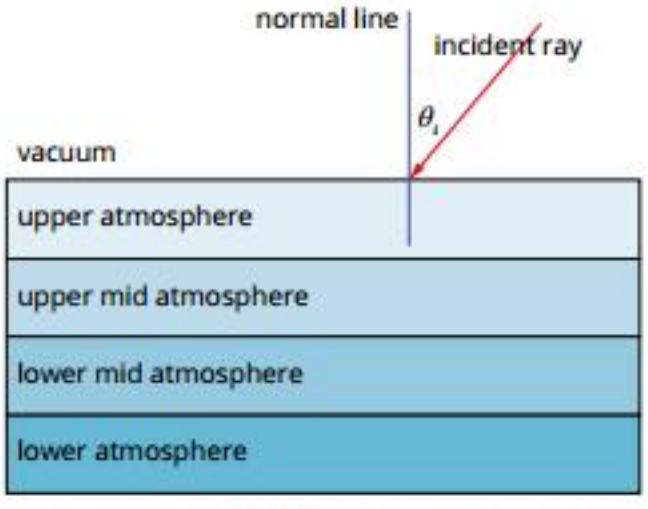
Write a correct statement comparing the apparent depth and true depth of a swimming pool and include an explanation or justification for your thinking.

Thinking	Working
Incident light rays travelling upwards from the bottom of the pool refract at the water-air boundary. Light travels faster in air than water. The light rays refract away from the normal entering the observer's eye at a different (shallower) angle compared to the incident light rays. The observer sees the refracted rays of light.	Light rays from an object speed up in air, so the rays refract away from the imaginary normal line (vertical line) at the boundary. The image is seen to be shallower than the object. In this case the object is the bottom of the swimming pool.  Therefore the apparent depth as seen by the observer is shallower than the true depth of the swimming pool.

➤ Try yourself 9.4.3

REFRACTION OF LIGHT AND APPARENT POSITION

Sunlight is travelling through space (assume a vacuum) when it approaches the Earth's upper atmosphere, which is slightly denser than space. A single light ray strikes the boundary (interface) between the vacuum of space and the upper atmosphere at an arbitrary angle θ_i. The light ray refracts at this first boundary and continues to pass through the four different layers shown in the diagram below. Assume the atmosphere becomes denser as altitude decreases, therefore slowing the light ray at each boundary.



a Draw the path of the ray of light as it continues to travel through each atmospheric layer until it reaches the lower atmosphere.

b Comment on the effect of the different layers of the Earth's atmosphere on the path of the light ray.

c Considering the path of light drawn in part (a) discuss what that could mean for the observed position of stars in the sky.

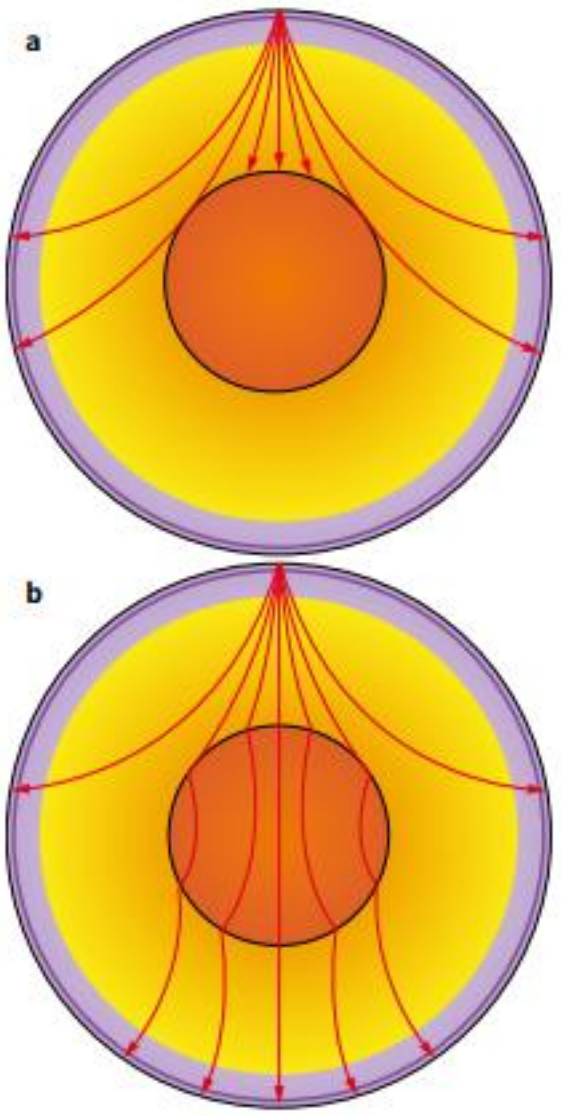


FIGURE 9.4.11 The path travelled by (a) seismic S-waves and (b) seismic P-waves passing through the Earth

OTHER EXAMPLES OF REFRACTION

Any wave that undergoes a change in wave speed between two different media will refract. Two specific examples will be mentioned briefly, namely the refraction of seismic S-waves and P-waves in the Earth's crust and mantle; and the refraction of sound waves in the differing temperature layers of the Earth's atmosphere.

Seismic S-waves and P-waves

The speeds of both S-waves and P-waves depend on properties such as temperature and pressure of the media through which they travel. Seismic waves travel more quickly through denser materials and therefore generally travel more quickly with depth. When seismic waves travel between geological layers with differing seismic speeds, then refraction and reflection occur. These wave interactions provide evidence for the internal structure of the Earth.

Figure 9.4.11 shows what happens when S-waves and P-waves travel through the Earth. S-waves travel through solid only (transverse waves) and the faster-moving P-waves travel through liquids and solids. Notice how both waves refract when travelling through the Earth's mantle.

Sound waves

Have you ever noticed that some sounds can be heard over long distances at particular times of the day? Fishermen notice this phenomenon very early in the morning as the Sun starts to rise and warm the upper layers of the air above a cool lake. Sounds from the other side of the lake can be heard, which cannot be heard later in the morning. This can be explained by Huygens' principle and the effect of differing air temperatures on the speed of sound.

The upper layers of air are warmer in the early morning due to the sunlight warming the air particles. The lower layers of air are cooler due to the cool surface of the lake. The layers of warmer air above cooler air are called a **thermal inversion**, as shown in Figure 9.4.12. Sound waves travel faster in warmer air than in cooler air. Following Huygens' principle, the upper part of the wavefront acts as a point source for secondary wavelets and travels a greater distance than the lower part of the wavefront. The effect is that sound waves refract downwards back to Earth as the secondary wavelets pass through the layers of air at different temperatures.

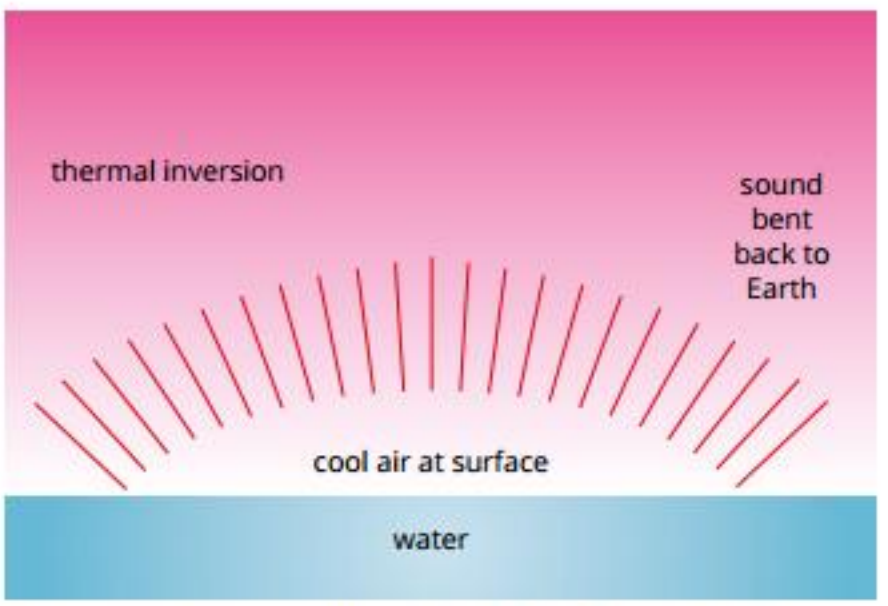


FIGURE 9.4.12 A thermal inversion refracts sound waves back down to Earth.

9.4 Review

SUMMARY

- Huygens' principle is the theoretical basis for explaining wave propagation in two dimensions.
- Refraction is the change in direction of a wave due to a change in speed of the wave.
- When a wave travels from one medium to another, the direction of propagation of the wave can either refract towards the normal line (slow down) or refract away from the normal line (speed up).
- The angle of incidence is the angle between the incident ray and the imaginary normal line.
- The angle of refraction is the angle between the refracted ray and the imaginary normal line.
- The velocity of light and the wavelength of light can be affected by the type of medium; however, the frequency does not change.
- The wave model of light can explain phenomena such as the apparent position of objects that are under the water, and the shape of the Sun at sunrises and sunsets.
- Seismic waves refract in the mantle of the Earth with increasing depth and increasing speeds of both P-waves and S-waves.
- Sound waves refract back towards Earth, when a thermal inversion occurs in the atmosphere.

KEY QUESTIONS

Describe

1 Describe what happens when waves are refracted.

2 Draw a diagram showing how waves slowing down in the second medium bends the waves at the boundary between the two media.

Apply

3 Use Huygens' principle to draw the wavefront of the plane wave shown after one period.

4 Draw ray diagrams for the following situations. In each diagram, include the boundary (solid line) and the normal (dotted line) in your diagrams.

a Light is coming from a medium less optically dense to a medium more optically dense. Draw a ray diagram showing how the light bends at the boundary between the media.

b Light travels faster in the second medium compared with the first medium. Draw a diagram of the boundary of these two media showing the angle of refraction.

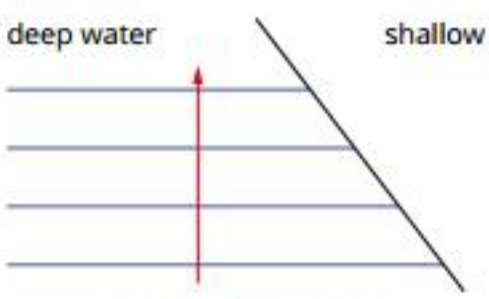
5 For the following situations, relate the size of the angle of incidence to the angle of refraction.

a Waves speed up at a boundary between two media.

b Light is travelling from air (less optically dense) to water (more optically dense).

Analyse

6 Water waves are travelling from deep water up the page and into shallow water, as shown in the diagram. The wavefronts in the deep water, and the boundary between the deep and shallow water are sketched already. Sketch the wavefronts refracting in the shallow water, include a ray for direction. Label the angle of incidence θ_i and the angle of refraction θ_r.



7 Assess whether these statements are true or false regarding different types of waves and the angles of incidence and refraction. Rewrite the false statements to make them true.

a When light rays refract away from the normal line at a boundary between two different media, the light wave is travelling faster in this new medium.

b Sound waves will always refract down towards the Earth's surface, as the higher part of the wavefront travels faster than the lower part of the wavefront.

c The setting and rising Sun appears flatter than the afternoon Sun because light from the higher part of the Sun refracts more than that from the lower part of the Sun. The observed effect is that the top of the Sun is lowered more than the bottom of the Sun.

d The speeds of both seismic waves depend on the properties, such as temperature and pressure, of the media through which the seismic waves pass. Seismic waves travel more quickly through denser materials and therefore generally travel more quickly with depth.

9.5 Diffraction

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe 'diffraction'
- recall the relationship between the wavelength and the aperture width for significant diffraction to occur
- apply Huygens' principle to sketch the wavefronts after passing through an opening or aperture

When light passes through an opening such as a window into a darker room, you expect to see the sharp shadow of the window on the floor of the room. You do not expect to see light bend around corners or appear in other parts of the room. When sound passes through a doorway, you expect it to travel to all parts of the room, to spread out and for all observers to hear the sound in all parts of the room.

So, what is different between the behaviour of sound waves and light waves? Why does one wave appear to travel in a straight line, as a light ray, and the other wave seems to bend around corners and travel in all directions? To fully understand these observations, you need to consider the wave property of diffraction.

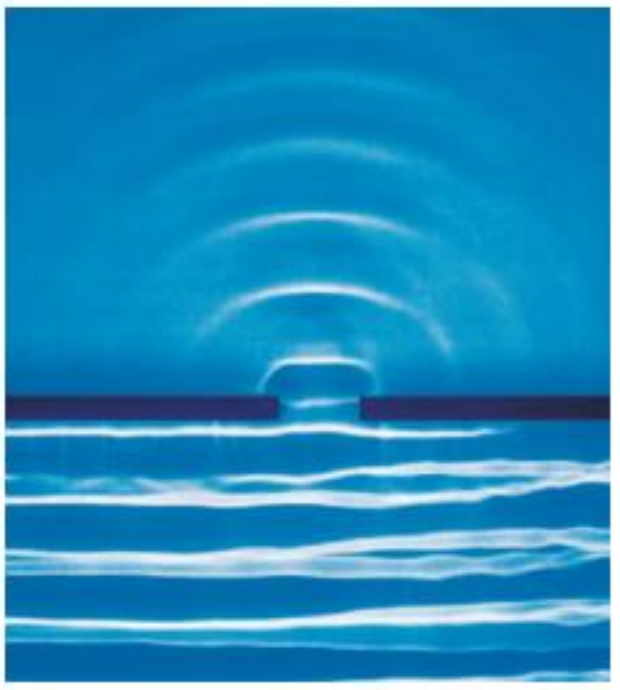


FIGURE 9.5.1 Water waves bend as they pass thorough an aperture. Sound waves will diffract as well, allowing you to hear around corners.

DIFFRACTION

When a plane (straight) wave passes through a narrow opening or **aperture**, it **diffracts** (bends), as shown in Figure 9.5.1. Waves will also bend as they travel around obstacles. This kind of 'bending' phenomenon is known as diffraction. Huygens' principle, introduced in Module 9.4, will be used to explain the nature of wave propagation around obstacles and through narrow openings.

Huygens' principle can be used to explain the shape of diffracted waves. Wave fronts approach a barrier with three openings. Every point along a wave front is a source of a new wavelet front. As the wave front reaches the openings, a point along the front passes through the gap, diffracting and starting a spherical wavelet front. As the spherical wavelets travel outwards, they intersect with each other and produce a new wave front which is curved (Figure 9.5.2a). The same diffraction pattern occurs when the gap is larger and several points along the wavefront move through the gap (Figure 9.5.2b).

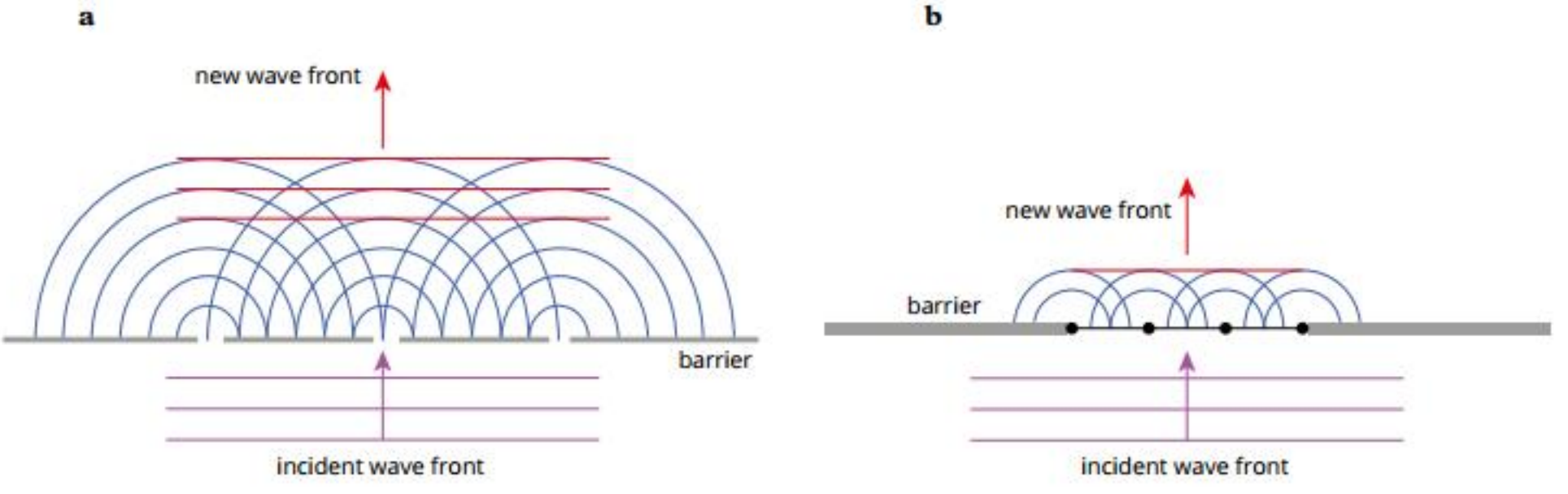


FIGURE 9.5.2 Huygens' principle shows the origin of curvature of a diffracted wave for (a) a series of small gaps in a barrier and (b) a larger gap in a barrier.

Diffraction is significant when the size of the opening or obstacle is similar to the wavelength of the wave. This means that the diffraction of light is difficult to observe because the wavelength of light is very small.

Light waves range in wavelength from around 700 nm for red light to about 400 nm for violet light. One nanometre (1 nm) is equal to 10^{-9} m or a one-millionth of a millimetre. This means that light waves are all less than one-thousandth of a millimetre in length. Light waves do not encounter many naturally occurring structures of this size, so diffraction is not easily observed. Usually, diffraction occurs with artificially constructed materials such as CDs or commercially produced diffraction gratings (Figure 9.5.3).

Sound waves range in frequency from 2 Hz to about 20 000 Hz for normal hearing. This corresponds to wavelengths from 17 mm to about 170 m. Any opening corresponding to these wavelengths, such as windows or door openings, could result in the diffraction of sound waves being observed. Or, more importantly, some sound waves could result in diffraction and others could not. To compare the wavelength of the sound wave produced and the size of the opening, you may need to use the wave equation $f = \frac{v}{\lambda}$.

FIGURE 9.5.3 The way information is printed on a CD or DVD means that it creates structures small enough to cause light to diffract.

- If the wavelength of a wave is a similar size or larger than the width of a gap ($\lambda \geq w$), then significant diffraction occurs and the waves emerge as circular waves.
- If the wavelength of a wave is smaller than the width of a gap ($\lambda < w$), then less diffraction occurs.

Diffraction and slit width

When waves are diffracted around an opening, the size of the gap affects the degree of diffraction. If the wavelength is much smaller than the gap or obstacle, then the degree of diffraction is less. For example, Figure 9.5.4 shows the diffraction of water waves in a ripple tank.

In Figure 9.5.4a, the gap is similar in size to the wavelength, so significant diffraction occurs and the waves emerge as circular waves. In Figure 9.5.4b, the gap is much bigger than the wavelength, so diffraction only occurs at the edges. Wavelengths comparable to, or larger than, the diameter of the obstacle or gap will produce significant diffraction.

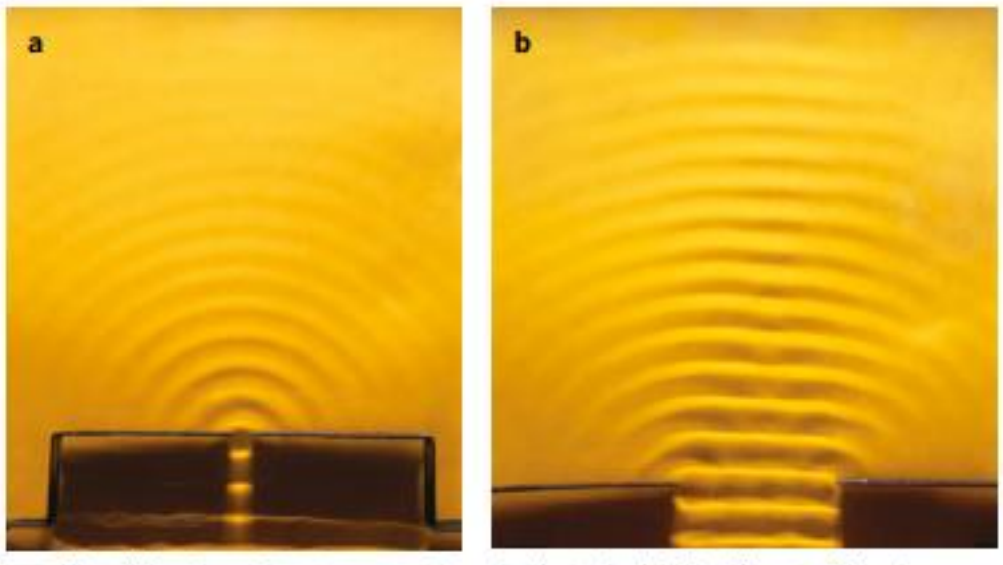


FIGURE 9.5.4 The diffraction of water waves in a ripple tank. (a) Significant diffraction occurs when the wavelength approximates the slit width ($\lambda \approx w$). (b) As the gap increases ($\lambda << w$), diffraction occurs mainly around the edges. It becomes less obvious but is still present.

Worked example 9.5.1

DIFFRACTION

A red neon laser emits light with a frequency of 4.5×10^{14} Hz. A white light source is a mixture of frequencies from 4.3×10^{14} Hz to 7.5×10^{14} Hz, with an average frequency of about 5.5×10^{14} Hz. Both light sources travel in air with a speed of 3.00×10^{8} m s^{-1}.

Calculate the wavelength, using the wave equation, and the dimension of the opening for diffraction of these waves to occur. Give answers for both light sources in mm.

Thinking	Working
For the neon laser the frequency is 4.5×10^{14} Hz. Rearrange the wave equation to solve for λ. When converting from m into mm, multiply the number by 1000. This is the size of the slit for diffraction to occur.	$\lambda = \frac{v}{f}$ $= \frac{3.00 \times 10^8}{4.5 \times 10^{14}}$ $= 670 \times 10^{-9}$ m $= 670$ nm $= 6.7 \times 10^{-7}$ m $= 0.00067$ mm
For white light the average frequency is 5.5×10^{14} Hz. Rearrange the wave equation to solve for λ. The average wavelength is about 545 nm. When converting from m into mm, multiply the number by 1000. Therefore, this is the size of the slit needed for diffraction.	$\lambda = \frac{v}{f}$ $= \frac{3.00 \times 10^8}{5.5 \times 10^{14}}$ $= 545 \times 10^{-9}$ m $= 545$ nm $= 5.5 \times 10^{-7}$ m $= 0.00055$ mm

➤ Try yourself 9.5.1

DIFFRACTION

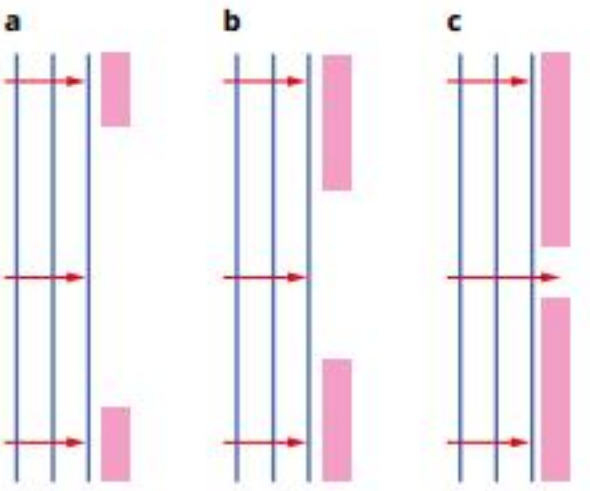
A piano produces a range of notes from 28 Hz to about 4200 Hz. The sound waves coming from a piano are diffracted around a doorway into the hallway. What dimensions must the doorway opening have? Assume the average frequency of sound heard coming from the piano is about 2000.0 Hz and the speed of sound in air is 340 m s^{-1}.

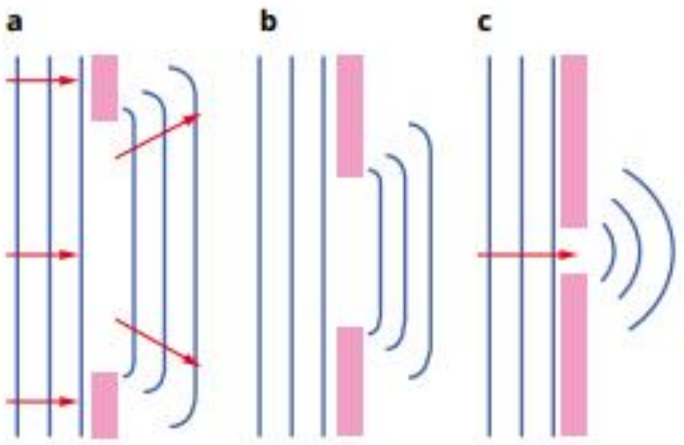
Explain what this calculation suggests about the sound waves heard in the hallway, and the diffraction of these waves.

Worked example 9.5.2

DIAGRAMS OF DIFFRACTION

In the three diagrams below, wavefronts are travelling towards openings of three different sizes. For each diagram, draw the wavefront pattern after passing through the opening. Take care to compare the wavelength, λ, of the wavefronts and the size of the opening, w.

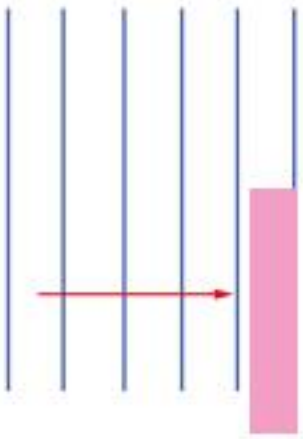


Thinking	Working
Compare the wavelength of the waves, λ, and the size of the opening, w. **a** The width of the gap is much greater than the wavelength, so diffraction occurs at the edge of the opening only. **b** The width of the gap is smaller, so more diffraction occurs. **c** The width of the gap is similar to the wavelength, so diffraction occurs, with circular concentric wavefronts.	

➤ Try yourself 9.5.2

DIAGRAMS OF DIFFRACTION

A wave travelling to the right strikes a barrier or edge, as shown in the diagram below. Sketch the resulting wavefront of the wave as the wave continues to travel past this barrier.



9.5 Review

SUMMARY

- When a plane (straight) wave passes through a narrow opening or meets a sharp object, it experiences diffraction.
- Significant diffraction occurs when the wavelength of the wave is similar to, or larger than, the size of the diffracting object.
- Diffraction bends the wave around the edges of the opening. If the opening is similar in size to the wavelength, this produces a circular wave.
- An application of Huygens' principle allows us to sketch the wavefronts after passing through an opening.

KEY QUESTIONS

Describe

1 Describe 'diffraction' and recall two examples where diffraction occurs.

2 Recall the conditions between the wavelength, λ, of a wave and the width of the opening, w, for diffraction to occur.

Apply

3 Identify which of the statements a–e are true and which are false. Rewrite the false statements to make them true.

a Visible light waves have a frequency range from 400 Hz to 800 Hz and require an opening with a width of about 10^{-2} mm for diffraction to occur.

b Water waves with a frequency of 0.2 Hz and a speed of 0.5 m s^{-1} diffract around an opening with a width of 2.5 m.

c An acoustic guitar produces a middle C note with a frequency of 261.6 Hz. An opening with a width of 3.1 m or larger would cause this sound wave to diffract.

d A comparison between light waves and diffraction opening widths suggests that red light with a longer wavelength will diffract with a smaller opening width, compared to violet light.

e Any wave will only diffract if the dimensions of the opening, w, and the wavelength of the wave, λ, are identical.

4 State the size opening width, in mm, that would be needed in order to produce significant diffraction of red light (wavelength of approximately 700 nm) in a diffraction experiment.

5 The entrance to small harbour is 120 m wide. During a storm, the ocean waves have a wavelength of 130 m. What shape will the waves make when they enter the harbour?

Analyse

6 A morpho butterfly wings are covered in tiny ridges which diffract blue light, giving the butterfly its blue colour. To produce significant diffraction what is the approximate spacing of the ridges. (Blue light has a frequency of 6.66×10^{14} Hz.)

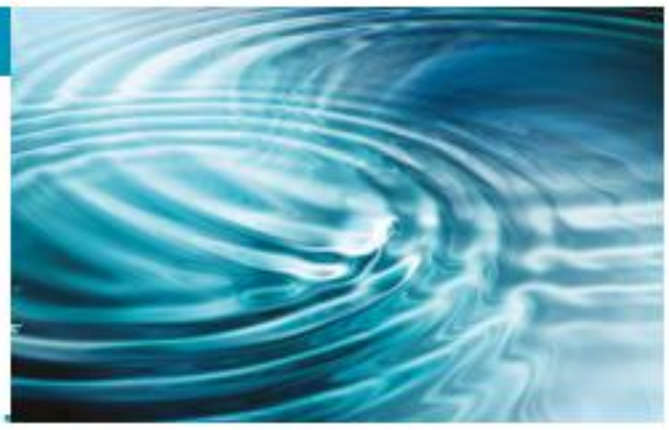
7 Most doorways are approximately 1.0 metre wide. A guitar player produces a middle C note (C_4) with a frequency of 262 Hz and a listener is standing to one side of the doorway opening, not in direct line of the guitar player. Assess whether the listener would be able to hear this note due to the sound wave diffracting around the edge of the doorway. Assume the speed of sound in air is 340 m s^{-1}.

8 Describe the differences between refraction and diffraction.

9.6 Interference and superposition

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the principle of superposition
- apply the principle of superposition to determine the resultant amplitude of two waves
- explain constructive and destructive interference of two simple waves
- apply the path difference relationship between two sources to determine whether constructive or destructive interference occurs.



The characteristic sounds of musical instruments, the human voice, or a combination of both at a musical concert, is due to the interaction of multiple mechanical waves. The interaction of these mechanical waves results in superposition. Superposition can be applied to waves whenever two or more waves travel through the same medium at the same time.

SUPERPOSITION

Imagine two transverse mechanical waves travelling towards each other along a string (Figure 9.6.1a). When the crest of one wave coincides with the crest of the other, the resulting displacement of the string is the vector sum of the two individual displacements (Figure 9.6.1b). The amplitude at this point is increased and the shape of the string resembles a combination of the two pulses. After they interact, the two pulses continue unaltered (Figure 9.6.1c). The resulting pattern is a consequence of the **principle of superposition**.

When a pulse with a positive displacement meets a pulse with a negative displacement (Figure 9.6.2a), the resulting wave will have a smaller amplitude (Figure 9.6.2b). As in Figure 9.6.1, the resulting displacement of the string is the vector sum of the two individual displacements. The resulting pattern follows the principle of superposition. **Superposition** is also known as **interference** and the terms are often used interchangeably.

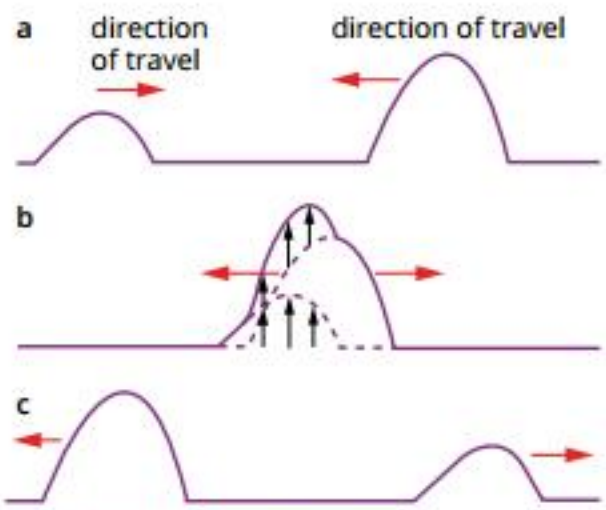


FIGURE 9.6.1 (a) Two wave pulses approach each other. (b) The pulses interact, and constructive superposition occurs. (c) After the interaction, the pulses continue unaltered; they do not permanently affect each other.

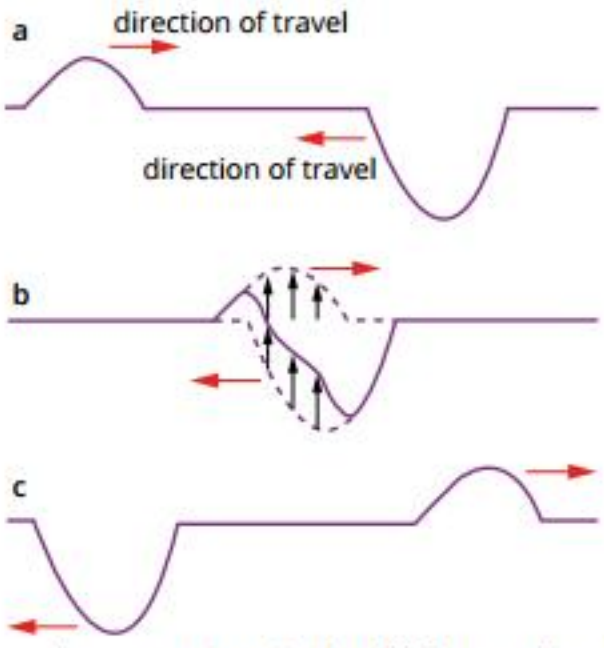


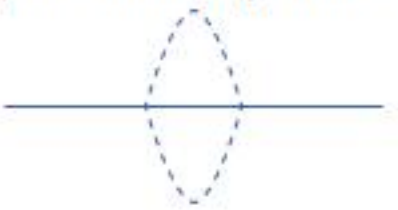
FIGURE 9.6.2 (a) Two wave pulses approach each other. (b) Superposition of the waves in the string shows destructive superposition. (c) The pulses continue unaltered. As in constructive superposition, the waves do not permanently affect each other.

Worked example 9.6.1

SUPERPOSITION

Two pulses travelling in a string are moving towards each other as shown below. As the pulses move towards each other they will interfere, producing an overlapping interference wave pattern and continue to move in the original directions. Draw the resulting interference pattern (when the pulses overlap) and the pulses after interference, for each example.

a pulses with identical amplitudes travelling towards each other

Thinking	Working
The diagram shows two pulses with the same amplitude but the pulse on the right is inverted (or upside down). When these two pulses overlap, the two pulses will destructively interfere, as the displacement of the pulse on the left will cancel out the displacement of the pulse on the right. After interference the pulses will continue to travel with the same amplitude and speed as before superposition (if you ignore energy losses to the string).	pulses destructively interfere  pulses move away from other

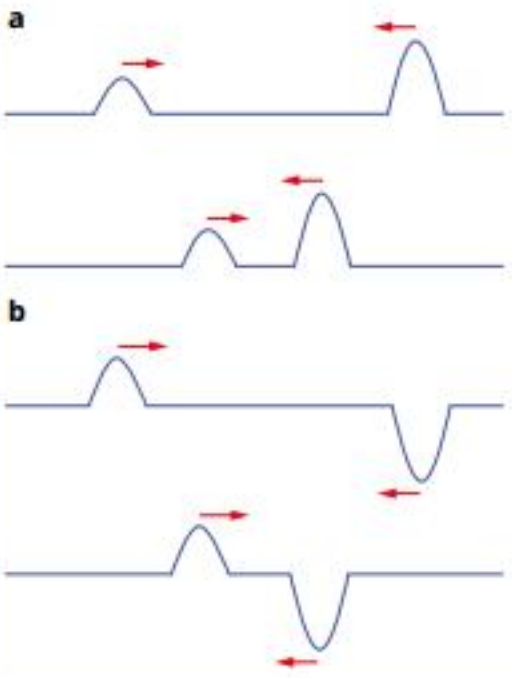
b pulses with differing amplitudes travelling towards each other

Thinking	Working
The diagram shows two pulses with different amplitudes. The pulse on the left has roughly twice the amplitude of the pulse on the right. When these pulses overlap, the two pulses will interfere through the addition of the separate pulse displacements. The displacement of the pulse on the left is larger and will produce an interference pulse pattern with a lower crest, due to superposition. After interference the pulses will continue to travel with the same amplitude and speed as before superposition (again if you assume no energy losses in the string).	pulses interfere pulses move away from other

➤ Try yourself 9.6.1

SUPERPOSITION

Two pulses are travelling along an elastic string (where no energy is lost to the string). In the diagrams for parts **a** and **b** below, the pulses are shown travelling towards each other during successive time intervals t_1 and t_2. Draw the pulse patterns in the string during and after interference between these pulses, for each diagram. Assume each time interval is identical and the pulses are travelling with a constant speed, v.



INTERFERENCE

When two waves meet and superimpose, there will be places where constructive interference occurs and places where destructive interference occurs.

- **Constructive interference** is shown in Figure 9.6.1 (page 365), in which the two waves added together to produce a wave of larger magnitude.
- **Destructive interference** is shown in Figure 9.6.2 (page 365), in which positive and negative displacements produce a wave of smaller magnitude.

Although the wave pulses interact when they meet, passing through each other does not permanently alter the shape, amplitude or speed of either pulse. Just like transverse waves, longitudinal waves will also be superimposed as they interact.

The effects of superposition can be seen in many everyday examples. The ripples in the pond in Figure 9.6.3 were caused by raindrops hitting the pond. Where two ripples meet, a complex wave results from the superposition of the two waves, after which the ripples continue unaltered. Similarly, in a crowded room, all the sounds reaching your ear have been superimposed, so that one complex sound wave arrives at the eardrum.

Superposition is important both theoretically and practically in the formation of complex sounds. Imagine two single-frequency sound waves, or pure tones, one of which is twice the frequency of the other. The two individual waves are added together to give a more complicated resultant sound wave, as shown in Figure 9.6.4. The sound wave with a greater amplitude will be the predominant sound heard. The quieter, higher frequency sound will combine with the louder sound to create the complex sound that you hear. Note that for Figure 9.6.4, a transverse wave is used to depict the sound wave. The crests represent compressions (areas of high pressure) and the troughs represent rarefactions (areas of low pressure). Showing longitudinal waves in this way makes features such as period, and therefore frequency, easier to see.

FIGURE 9.6.3 The ripples from raindrops striking the surface of a pond behave independently, regardless of whether they cross each other or not. Where the ripples meet, a complex wave will be seen as the result of the superposition of the component waves. After interacting, the component waves continue unaltered.

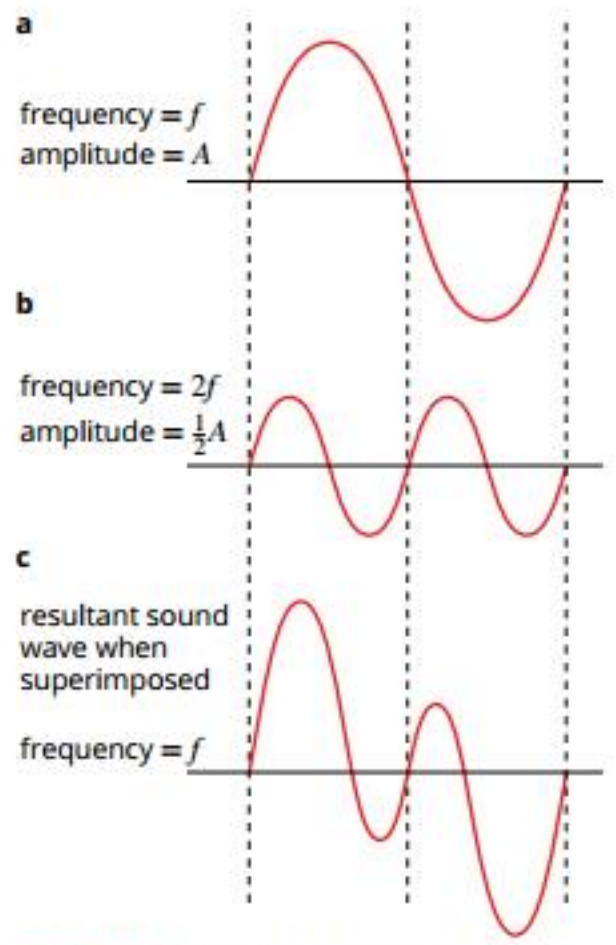
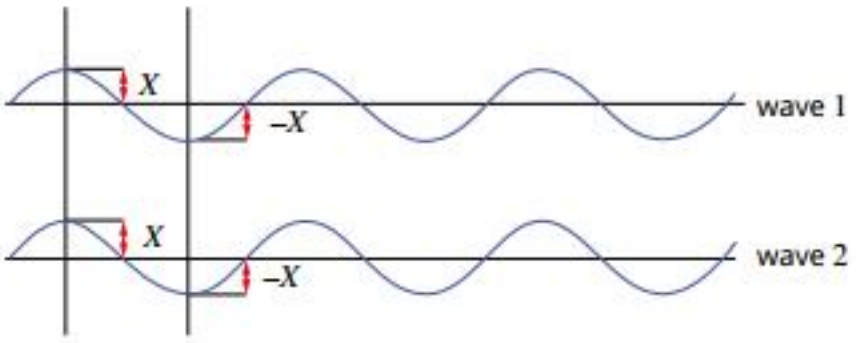


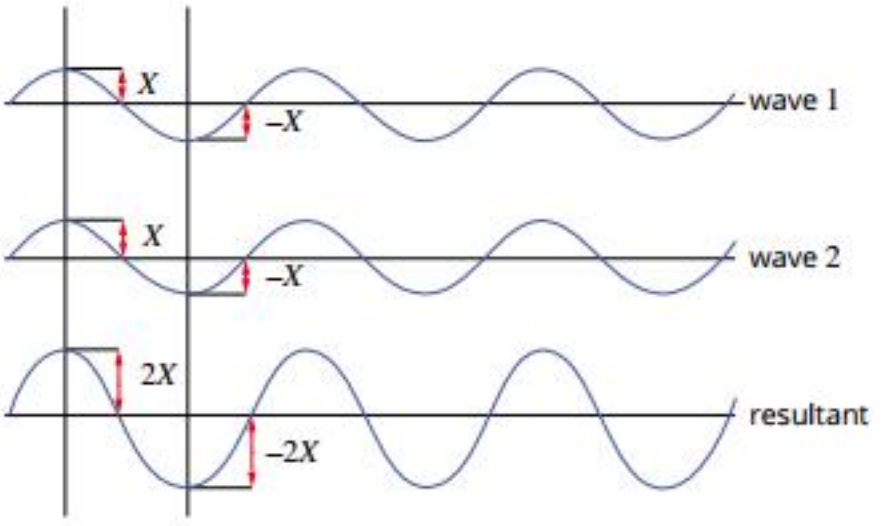
FIGURE 9.6.4 Two sound waves, one twice the frequency of the other, produce a complex wave of varying amplitude when they are superimposed.

Worked example 9.6.2

INTERFERENCE

The graph shows two identical waves that arrive in phase. Note identical amplitudes and wavelengths, and all points on both waves are in phase. Use the principle of superposition to sketch the resultant wave produced from the interference of wave 1 and wave 2.

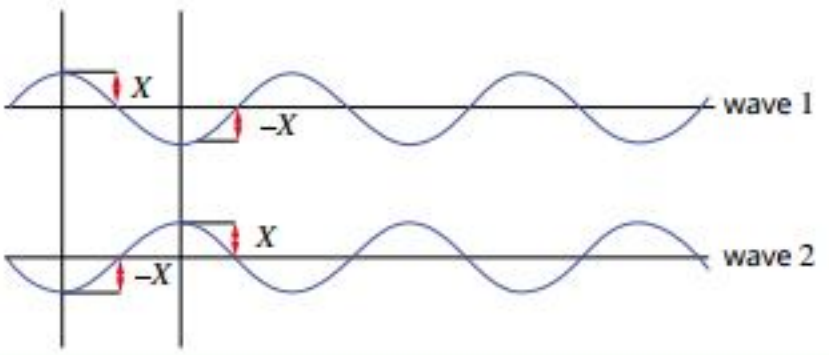


Thinking	Working
The crests of wave 1 correspond to the crests of wave 2. The troughs also correspond. The wavelengths are identical as are the amplitudes, X of each wave. The principle of superposition adds the displacements of waves at the same position or point. This is an example of complete constructive interference, with the resultant wave pattern having double the amplitude of the original waves. The resultant wave results from the addition of the displacements of wave 1 and wave 2. The resultant wave has twice the amplitude of the individual waves.	

➤ Try yourself 9.6.2

INTERFERENCE

The graph shows two identical waves that arrive exactly out of phase (or have a phase difference of 180°). Note identical amplitudes and wavelengths, but all points on the waves are out of phase. Use the principle of superposition to sketch the resultant wave produced from the interaction of wave 1 and wave 2.



Interference from two point sources

Interference from two point sources occurs when waves from both sources meet up and interfere. The resultant wave pattern at this point is dependent on the phase of each wave. If two crests meet up at a point, then the resultant wave at that point will be due to the constructive interference of both waves. This is also the case if two troughs meet at the same point, which produces a larger resultant wave due to constructive interference between the two wave sources.

In Figure 9.6.5, two identical waves produced from sources S_1 and S_2 combine at a point some distance away from the individual sources. The point at which the two sources combine is exactly six wavelengths from S_1, and eight wavelengths away from S_2. If both S_1 and S_2 oscillate at the same frequency and have the same amplitude and wavelength, then the two waves will undergo complete constructive interference at this point.

Distance from $S_1 = 6\lambda$

Distance from $S_2 = 8\lambda$

The **path difference** between the two sources = 2λ (an integral number of wavelengths).

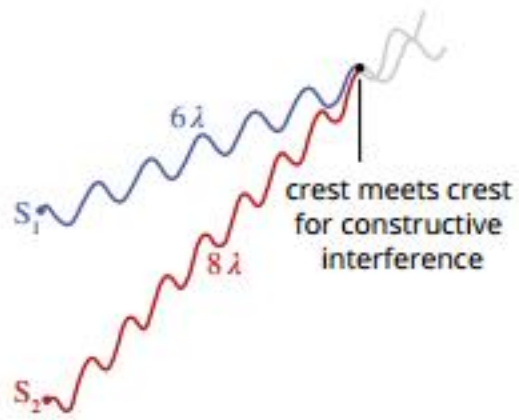


FIGURE 9.6.5 At a point a distance of 6λ from S_1 and 8λ from S_2 the two waves will interfere constructively. The path difference between the two waves is 2λ.

In Figure 9.6.6, two waves, produced from sources S_1 and S_2 combine at a point some distance away from the individual sources. The point at which the two sources combine is exactly a distance equal to three-and-a-half wavelengths away from S_1, and four wavelengths away from S_2. If both S_1 and S_2 oscillate at the same frequency and have the same amplitude and wavelength, then the two waves will undergo complete destructive interference at this point.

Distance from $S_1 = 3.5\lambda$

Distance from $S_2 = 4\lambda$

The path difference between the two sources = 0.5λ (not an integral number of wavelengths).

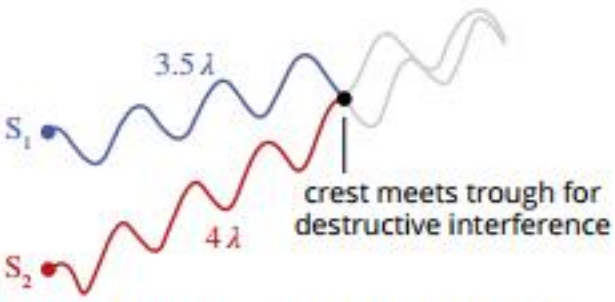


FIGURE 9.6.6 At a point a distance of 3.5λ from S_1 and 4λ from S_2 the two waves will interfere destructively. The path difference between the two waves is 0.5λ.

The conditions for complete constructive interference and complete destructive interference can be stated in terms of the path differences travelled by these identical waves.

In Figure 9.6.7, the darker lines represent crests from two identical sources S_1 and S_2, and the lighter lines represent troughs. This figure represents either transverse or longitudinal waves.

The red lines represent complete constructive interference at:

- $m = 0$ (zero path difference)
- $m = 1$ (path difference = 1λ)
- $m = 2$ (path difference = 2λ).

The blue lines represent complete destructive interference at:

- $m = 0.5$ (path difference = 0.5λ)
- $m = 1.5$ (path difference = 1.5λ)
- $m = 2.5$ (path difference = 2.5λ).

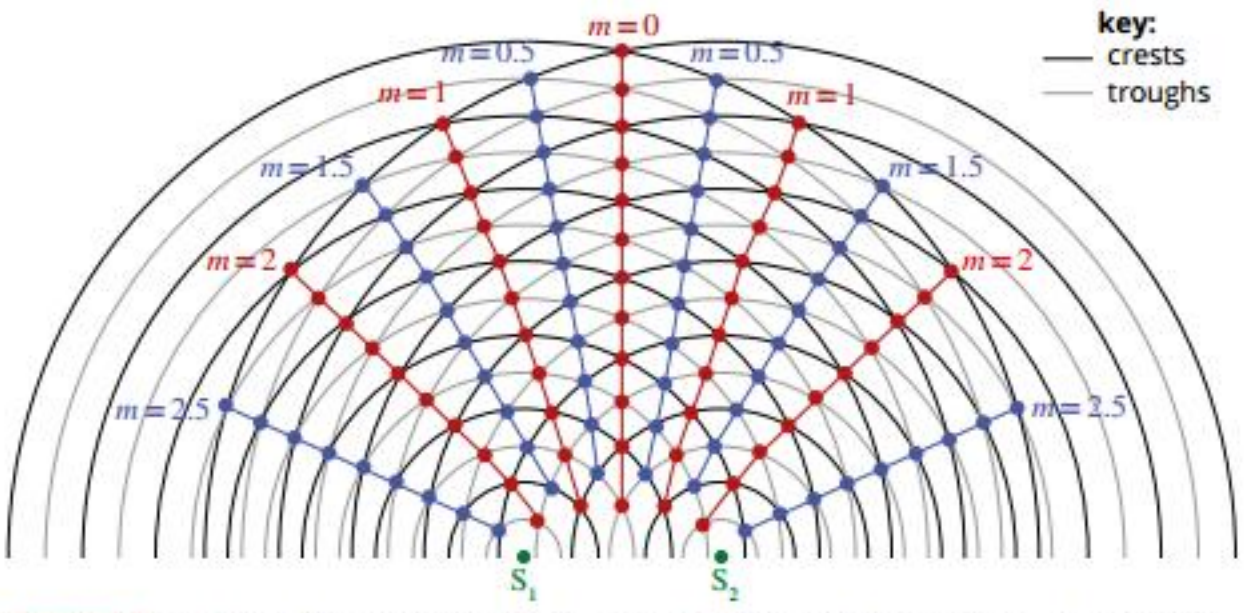


FIGURE 9.6.7 The path difference between two sources. If the path difference is $m = 0$, 1 or 2 (red lines), constructive interference is observed. If the path difference is $m = 0.5$, 1.5, 2.5 (blue lines), destructive interference is observed.

For two identical waves:

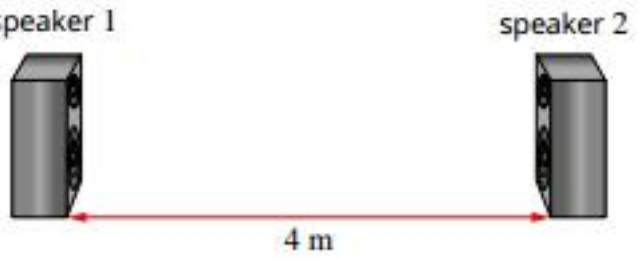
- **Constructive interference occurs when the path difference = $n\lambda$ ($n = 0, 1, 2, \ldots$).**
- **Destructive interference occurs when the path difference = $(n + \frac{1}{2})\lambda$ ($n = 0, 1, 2, \ldots$).**

Worked example 9.6.3

INTERFERENCE FROM TWO POINT SOURCES

Two loudspeakers are positioned exactly 4.0 m apart and facing each other, as shown below. The speakers are producing identical sounds (equal amplitude and phase) with a frequency of 340 Hz. A person sits halfway between the two speakers.

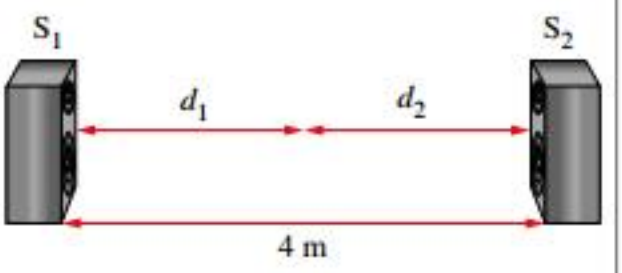
Assume the speed of sound in air is 340 m s^{-1}.



a Calculate the wavelength of these sound waves, using the wave equation.

Thinking	Working
Both the wave frequency and the wave speed are known. Rearrange the wave equation to determine the wavelength of these sound waves.	$\lambda = \frac{v}{f}$ $= \frac{340}{340}$ $= 1.0\,\text{m}$

b In terms of wavelengths, determine how far this person is from each loudspeaker.

Thinking	Working
A person sitting halfway between the speakers is 2.0 m from each speaker. This is exactly 2 whole wavelengths from each speaker.	 $d_1 = 2.0\,\text{m}$ and $d_2 = 2.0\,\text{m}$ $d_1 = 2\lambda$ and $d_2 = 2\lambda$

c Determine the path difference between the two sound waves travelling towards the person.

Thinking	Working
The two sound waves travel the same distance in opposite directions: $2\,\text{m} = 2\lambda$ Path difference is calculated by subtracting the paths travelled by each sound wave.	Path difference $= 2\lambda - 2\lambda = 0$

d Identify whether the interference pattern produced (at the person's position) is a point of complete constructive or destructive interference between the two loudspeaker sounds. Explain what the person would hear.

Thinking	Working
Refer to the interference conditions to determine whether complete constructive interference or complete destructive interference has occurred at this point. The two waves will meet at this point in phase. Constructive interference occurs.	Constructive interference occurs when the path difference $= n\lambda$ (where $n = 0, 1, 2, ...$). The person would notice constructive interference between the two sound waves, therefore the interference pattern would have twice the amplitude as the two individual travelling sound waves. So, they would hear a noticeable increase in loudness of sound.

➤ Try yourself 9.6.3

INTERFERENCE FROM TWO POINT SOURCES

A second person sits 0.50 m from one of the speakers in Worked example 9.6.3.

a Calculate how far away this person is from the other speaker.

b Determine how far this person is from the speakers, in terms of wavelength.

c Determine the path difference between the two sound waves travelling towards this person.

d Identify whether the interference pattern produced (at that person's position) is a point of constructive or destructive interference between the two loudspeaker sounds. Explain what the person would hear.

9.6 Review

SUMMARY

- The principle of superposition states that when two or more waves interact, the resultant displacement or pressure at each point along the wave will be the vector sum of the displacements or pressures of the component waves.
- The shape of the medium during interference between two or more waves requires that the principle of superposition be applied for every point along the medium.
- Complete constructive interference occurs when overlapping identical waves are in phase. Complete destructive interference occurs when overlapping identical waves are 180° out of phase.
- Complete constructive interference occurs when the path difference between two waves is $n\lambda$.
- Complete destructive interference occurs when the path difference between two waves is $\left(n+\frac{1}{2}\right)\lambda$.

KEY QUESTIONS

Describe

1 Describe the principle of superposition.

2 State the conditions between two identical waves for both destructive interference and constructive interference to occur.

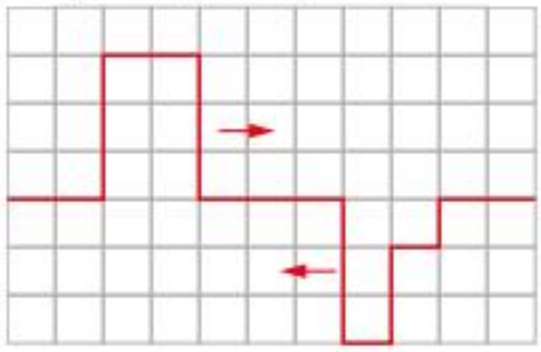
Apply

3 Describe what happens to the resulting wave when two identical waves have a phase difference of the following:

a 90°
b 180°
c 270°
d 360°

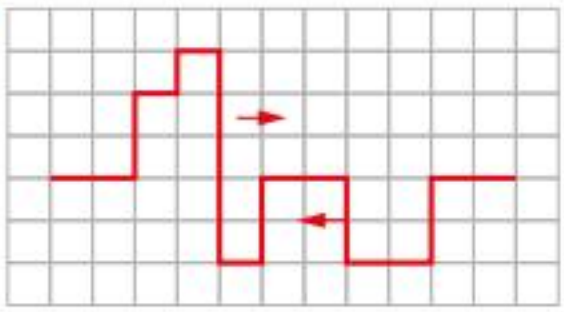
4 Draw a sequence of diagrams, for five time intervals, to demonstrate the principle of superposition for two pulses travelling towards each other in a light elastic string. Each time interval will advance the pulse shown by one complete pulse width. Use the first interval below and draw each subsequent time interval underneath the interval before.

5 The diagram below shows two pulses moving towards each other. Draw the result of these pulses at the moment they exactly overlap.

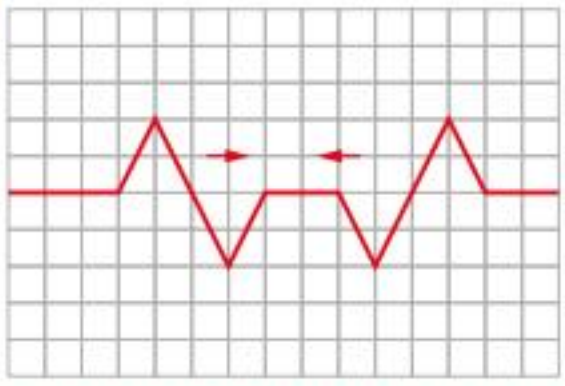


6 Draw the pulses below at a time 2s after they have been drawn if they are both moving at 1 square per second.

a



b



7 Determine which of the statements a–d are true and which are false. Rewrite the false statements to make them true.

- **a** Superposition will occur whether waves are in phase or not. If the waves are in phase they will produce a fixed interference pattern.
- **b** If two waves are in phase at a point then destructive interference occurs, and if the two waves are out of phase at a point then constructive interference occurs.
- **c** The principle of superposition occurs only for transverse waves, and not for longitudinal (or compression) waves.
- **d** One complete wave oscillation has a phase of 360°.

Analyse

8 Two loudspeakers both emit sounds with a frequency of 680 Hz. The two sounds have equal amplitude and phase. The speakers are 2.0 m apart and face each other. Assume the speed of sound waves in air is $340\,m\,s^{-1}$.

- **a** Calculate the wavelength of the sound waves.
- **b** The amplitude of each sound is given by the symbol *A*. Calculate the amplitude of the sound halfway between the speakers (ignoring any amplitude reduction with distance).
- **c** Identify the other distance from either speaker at which constructive or destructive interference will be observed. Hint: Use the path difference relationships to answer this.

9 Identical waves leaving from two sources S_1 and S_2 arrive at a position X. The waves from both sources have a wavelength of 2.8 m. The position X is 8.4 m away from the first source and 9.8 m away from the second source. State the path difference between the two waves arriving at point X in terms of the wavelength. Explain what is observed at point X.

10 Two identical point sources of light are emitting blue light ($\lambda = 460\,nm$). They are observed at a point P which is 2.00 µm from one source and 2.69 µm from the second source. What is the path difference between the two waves and what is observed at point P?

9.7 Standing waves

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand how standing waves are formed
- identify nodes and antinodes in a standing wave
- identify where standing waves occur in nature.
- explain the formation of standing waves.

The properties of reflection and superposition of waves allows you to understand how the interaction between two or more waves produces **standing waves.** Unlike travelling transverse or compression (longitudinal) waves, there is no net transfer of energy in a standing wave in an ideal situation. Standing waves are noticeable in stringed musical instruments such as the guitar, cello, violin or piano. Standing waves can also be heard in musical instruments that have an air column, such as the flute, oboe or the large organ pipes of a cathedral.

The different standing wave patterns and corresponding frequencies produced in stringed and air-column instruments will be studied in further detail in Chapter 10. This module deals with the qualitative understanding of how a standing wave is produced. A comparison between standing waves and travelling waves will allow an understanding of these two different types of wave.

Standing waves are formed from the superposition of waves. They occur when two waves of the same amplitude and frequency are travelling in opposite directions towards each other in the same string. Usually, one wave is the reflection of the other. Standing waves are responsible for the wide variety of sounds associated with speech and music.

FORMATION OF STANDING WAVES IN A STRING

In Module 9.3, you learnt that when a wave pulse reaches a fixed end, it is reflected 180° out of phase; that is, crests are reflected as troughs and troughs are reflected as crests.

Imagine creating a series of waves in a rope by shaking it vigorously. As you continue to shake the rope, waves will travel in both directions. The new waves travelling down the rope will interfere with those being reflected along the rope. This kind of motion usually creates a random pattern, and the waves die away quickly. Shaking the rope at just the right frequency, however, will create a new wave that interferes with the reflection in such a way that the two superimposed waves create a single, larger amplitude called a **standing wave**. A standing wave does not appear to be travelling along the rope. The rope simply seems to oscillate up and down with a fixed pattern, that is, it seems to be just 'flipping' up and down in a fixed pattern. This situation contrasts with a standard transverse wave, where every point on the rope has a maximum displacement at some time as the wave travels along the rope.

In Figure 9.7.1a–d, two waves (drawn in blue) are shown travelling in opposite directions towards each other along a rope. One of the waves is a string of pulses (shown as a solid line) and the other is its reflection (shown as a dashed line). The two waves superimpose when they meet; this is shown by the red line.

- In Figure 9.7.1a, at a particular point in time, the two waves are completely superimposed, resulting in a wave twice the original amplitude.
- In Figure 9.7.1b, after a time equal to $\frac{T}{4}$ (one-quarter of the period), the waves will each have moved $\frac{\lambda}{4}$, which means that they have moved $\frac{\lambda}{2}$ in relation to each other. The waves are completely out of phase and the resulting displacement is zero.

- In Figure 9.7.1c and Figure 9.7.1d, as more time goes by, the waves will continue to move past each other and completely superimpose again before cancelling again.
- In Figure 9.7.1e, the cycles shown in (a) to (d) form a standing wave. A standing wave swings between maximum displacements, creating antinodes (A) that are halfway between the stationary nodes (N). Regardless of the position of the component waves, these nodes stay in the same place. Successive nodal points are $\frac{\lambda}{2}$ apart, as are successive antinodal points.

The amplitude and frequency of each is the same, so the end result is a standing wave, as shown in Figure 9.7.1e. At the points where destructive interference occurs, the two waves totally cancel each other out and the rope will remain still. These are called **nodes**. Where the rope oscillates with maximum amplitude, constructive interference is occurring. These points on the standing wave are called **antinodes**.

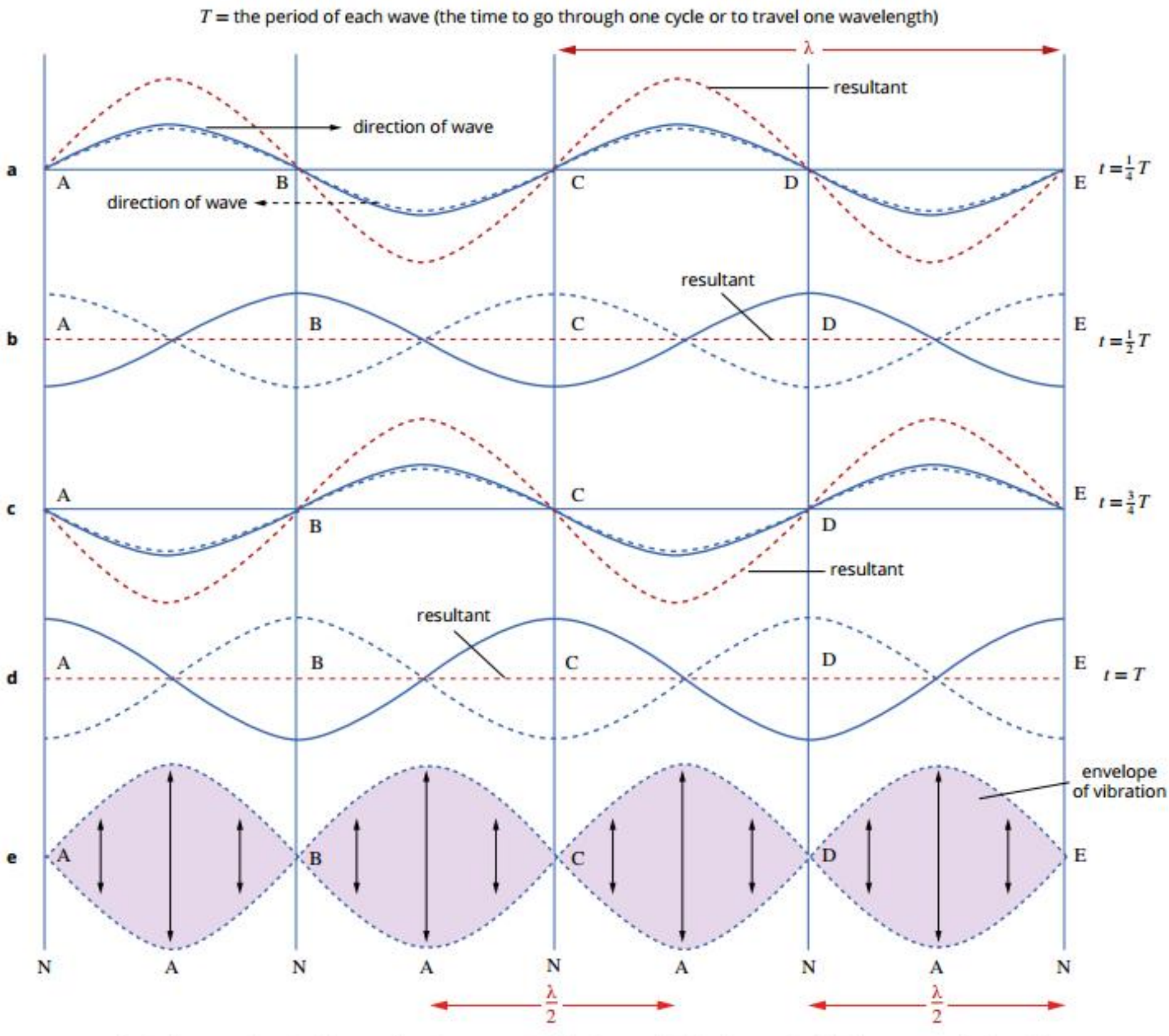


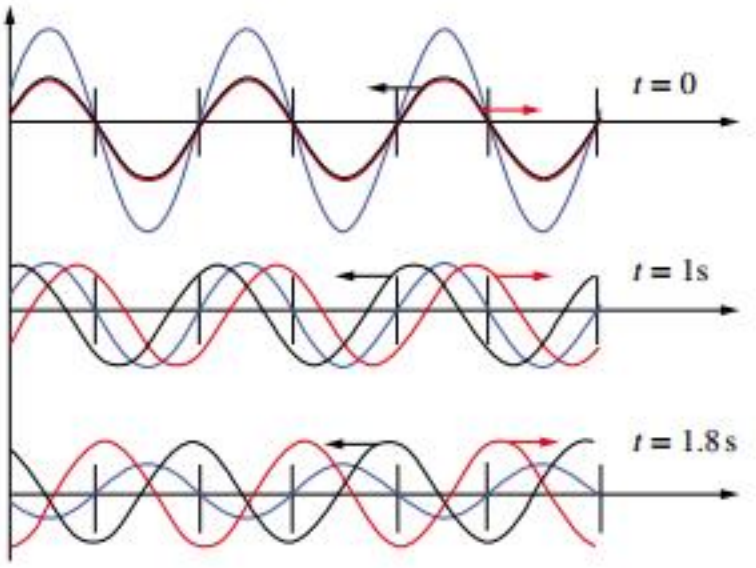
FIGURE 9.7.1 A standing wave is created in a rope from two waves travelling in opposite directions, each with the same amplitude and frequency

Worked example 9.7.1

STANDING WAVES

The formation of standing waves can be shown graphically with the aid of a series of diagrams. In the diagram below, the red wave is moving to the right and the black wave is moving to the left. The blue wave is the resultant wave pattern due to the superposition of these red and black waves. Each successive graph is at a later time.

State how the positions of the antinodes (crests, and troughs) and the nodes (zero resultant displacement) move or do not move for each successive graph. Comment also on the amplitude of the separate points on the resultant blue standing wave.



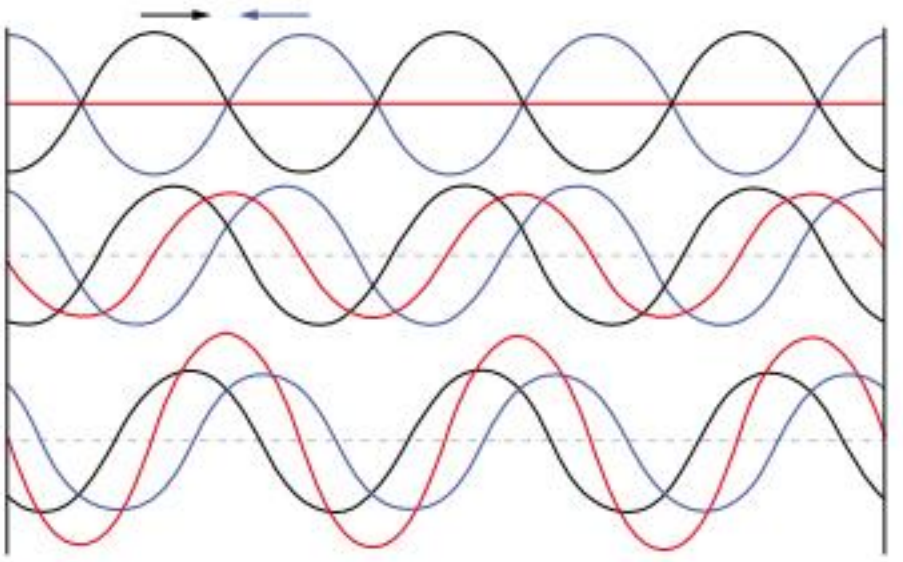
Thinking	Working
The red wave is moving to the right, and the green wave is moving to the left. The blue wave is the resultant wave pattern of the red and green waves. Look at the blue wave (the total displacement of the red and green waves) for each graph at identical positions.	The positions of antinodes (the crests and troughs) of the blue resultant wave do not change. The positions of the nodes (the points of zero displacement) of the blue standing wave do not change. The blue resultant wave pattern does not move to the left or the right but oscillates about the rest position. Its minimum displacement is zero and its maximum displacement is twice the amplitude of the red and green waves. The amplitude of the points on the blue standing wave varies at every point along the standing wave.

➤ Try yourself 9.7.1

STANDING WAVES

The diagram below is a time sequence showing two waves interacting at three different times. The black wave is the incident wave; it reflects off the fixed boundary or wall to the right. As it reflects it undergoes a 180° phase change. The interference pattern between the black incident wave and blue reflected wave is represented as the red standing wave.

For the third time sequence (the bottom one) label the nodes, antinodes, and the wavelength relationship between successive nodes on the standing (resultant) wave.



Nodes and antinodes in a standing wave remain in a fixed position for a particular frequency of vibration.

It is important to note that the formation of a standing wave does not mean that the string or rope itself is stationary. It will continue to oscillate as further wave pulses travel up and down the rope. It is the relative position of the nodes and antinodes that remain unchanged. It is also important to note that standing waves are not a natural consequence of every wave reflection.

Standing waves are only produced by the superposition of two waves of equal amplitude and frequency, travelling in opposite directions. They are a result of **resonance** and occur only at the natural frequencies of vibration, or **resonant frequencies**, of the medium. As well as existing in the everyday world, standing waves also occur at the subatomic level, which will be discussed in more detail in Unit 4.

Surface waves

The discussion in this module has been of two-dimensional standing waves, but standing waves may also form in three dimensions, such as in a section of Earth's crust. Standing waves will form as a result of resonance in any waveform.

Seismic surface waves travel along the boundary between materials, such as the Earth's crust and upper mantle. One type of surface wave is called the **Rayleigh wave**, or ground roll. Rayleigh waves are surface waves that travel as ripples with a motion like that of waves on the surface of water, although the restoring force is elastic rather than gravitational as it is for water waves. A phenomenon known as free oscillation of the Earth is the result of the superposition between two such surface waves travelling in opposite directions, creating a surface standing wave.

The first observations of free oscillations of the Earth were made during the 1960 Chile earthquake. Since then, thousands of harmonics have been identified.

Standing waves in air columns

It is possible to produce longitudinal stationary waves in air columns, which create the sounds associated with wind instruments. Blowing over the hole of a flute or the reed of a saxophone produces vibrations that correspond to a range of frequencies that create sound waves in the tube.

Most musical wind instruments can be simplified as long cylindrical air tubes that can be either open at both ends or open at one end and closed at the other. Blowing across a reed or opening has the effect of sending a pressure sound wave down the cylindrical tube and causing a reflected sound wave to interfere with the incident sound wave, producing a standing wave in the air column. The length of the tube will determine the frequency of the sounds that will resonate.

- At the closed end of a pipe, the reflected wave is 180° out of phase with the original wave (phase change). The closed end will not allow longitudinal motion in the air. This produces a node in the standing wave.
- At the open end of a pipe, the reflected wave is in phase with the original wave. This produces an antinode in the standing wave.

A series of standing wave patterns produced in a musical instrument open at both ends is shown in Figure 9.7.2. Nodes are indicated with the letter N, and antinodes are shown with the letter A. These wave patterns will be examined in more detail in Chapter 10.

Standing waves can also form from the superposition of sound waves, when they are reflected at the walls of a room. The reflected waves interfere with the incident waves, producing patterns of constructive and destructive interference. This leads to a standing wave. At the surface of a wall, air particles do not have room to move, so an air–displacement node occurs. The bunching up of particles near the surface of the wall creates a pressure antinode, which is a region of greater pressure. Therefore, the interference pattern for a pressure standing wave is a maximum or antinode at the surface of the wall and a node at the centre of the room.

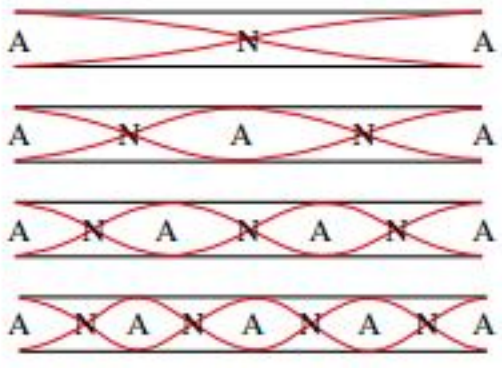


FIGURE 9.7.2 A series of standing wave patterns for a long cylindrical tube open at both ends

The two standing waves shown in Figure 9.7.3 are the longest wavelength standing waves in a room for a sound wave. The diagram on the left shows the air-pressure standing wave. The diagram on the right shows the air-displacement standing wave. Note that the pressure wave has a node where the displacement wave has an antinode, and vice versa. Both diagrams represent the standing wave for a note produced in the room.

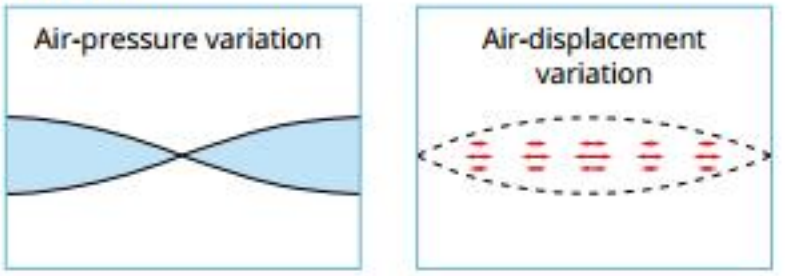


FIGURE 9.7.3 Air-pressure and air-displacement variation for a standing sound wave in a room

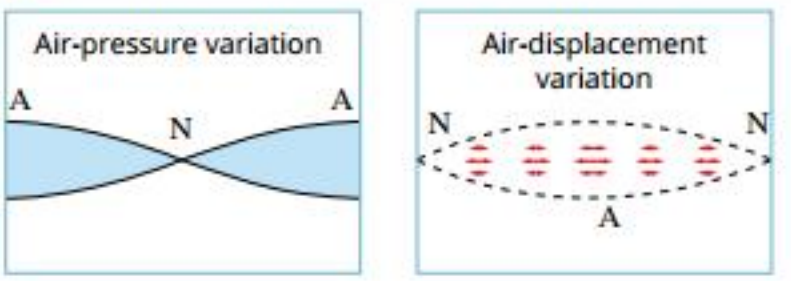
From this, the relationship between the room's dimensions and the wavelength of the longest wavelength standing wave can be found. The length of the room is equal to one-half of a wavelength for this standing wave pattern. Therefore, the longest wavelength standing wave in a room is twice the room's length.

Worked example 9.7.2

WAVELENGTHS OF STANDING WAVES

The longest wavelength standing wave forms in a room that is 10.0 m across.

a Draw a diagram showing the air-pressure standing wave and the air-displacement standing wave. Label the nodes and antinodes.

Thinking	Working
Air particles do not have room to move at the surface of a wall. Therefore, an air-displacement node occurs here. The bunching up of particles near the surface of the wall creates a greater region of pressure. Therefore, a pressure antinode occurs here.	

b Calculate the maximum wavelength of the standing wave.

Thinking	Working
For a standing wave, the distance between two successive nodes is equal to half a wavelength.	$10.0\,\text{m} = \frac{\lambda}{2}$ $\lambda = 2 \times 10.0$ $= 20.0\,\text{m}$

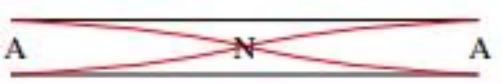
➤ Try yourself 9.7.2

WAVELENGTHS OF STANDING WAVES

A musical wind instrument that is open at both ends forms the standing wave shown in the diagram below. Nodes are indicated with the letter N, and antinodes are shown with the letter A.

a Determine whether this is an air-displacement or a pressure standing wave pattern.

b If the instrument is 20.0 cm long, calculate the maximum wavelength of the standing wave.



9.7 Review

SUMMARY

- Standing or stationary waves occur as a result of the interference between two waves of equal amplitude and frequency travelling in opposite directions.
- Points on a standing wave that remain still are called nodes.
- Points of maximum amplitude on a standing wave are called antinodes.
- The net transfer of energy in a standing wave is zero, unlike travelling waves.

KEY QUESTIONS

Describe

1 Recall how a standing wave is produced in a rope or string that is attached or fixed at the other end.

2 Recall the boundary conditions for an air-displacement standing wave in an air column. State where nodes and antinodes for air displacement will occur.

3 Can two waves, travelling opposite directions create a standing wave if they have different frequencies?

Apply

4 A transverse standing wave is produced on a rope. Explain whether the standing wave is actually standing still.

5 Explain the formation of nodes and antinodes on a standing wave.

6 A pipe, open at both ends, is 50 cm long. What is the longest wavelength of a standing wave in that pipe if both ends need to be antinodes?

Analyse

7 A pipe is closed at one end and open at the other. The closed end of the pipe results in a node, and the open end is an antinode. What is the smallest fraction or multiple of a wavelength that represents the distance between the node at the closed end and the antinode at the open end?

8 Using your answer to question 7, if a pipe with one closed end is 20 cm long, what is the wavelength of the standing wave?

9 Microwaves in a microwave oven have a frequency of 2.45 GHz and create a standing wave to vibrate water molecules and heat food. Use this to explain why when you microwave food, there can be cold and warm patches in the food. Explain how this is usually fixed.

Chapter review

09

KEY TERMS

absorption
amplitude
angle of incidence
angle of reflection
antinodes
aperture
apparent depth
compression
constructive interference
crest
destructive interference
diffraction
diffuse reflection
dissipate
frequency
Huygens' principle
image
incident ray
intensity
interference
law of reflection
longitudinal wave
mechanical waves
medium
natural frequency
nodes
normal
object
particles
path difference
period
phase
phase change
plane wave
principle of superposition
propagation
pulse
P-wave
rarefaction
ray
Rayleigh wave
real depth
real position
reflection
refraction
resonance
sinusoidal oscillation
standing waves
surface waves
superposition
S-wave
thermal inversion
transmitted
transverse wave
travelling wave
trough
tsunami
wavefront
wavelength

KEY QUESTIONS

Describe

1 A person is looking down at a fish below the surface of the water. Select the most correct statement regarding the apparent position and the real position of the fish.

A The real position and the apparent position are identical, as the reflected light from the water surface and the incident light make the same angle with the water's surface.

B The apparent position of the fish would be lower and closer than the real position.

C The real position would be lower in the water than the apparent position.

D The apparent position would be lower and further than the real position of the fish.

2 There are three quantities used to describe a light wave: speed, wavelength and frequency. Which quantities change when the light wave passes from glass to air?

A speed and wavelength

B speed and frequency

C wavelength and frequency

D speed, wavelength and frequency

3 Describe the difference between a pulse and a travelling wave.

4 State which of the following three waves is not a mechanical wave: sound waves, water waves, light waves. Give a reason for your response.

5 **a** A pulse is sent along a rope that is fixed at one end. Recall what happens to the pulse when it is reflected at the fixed end of the rope.

b A pulse is sent along a rope that is open at one end. Describe what happens to the pulse when it is reflected at the open end of the rope.

Apply

6 Visible light is between 400 and 700 nm. Which of these frequencies is possible for visible light?

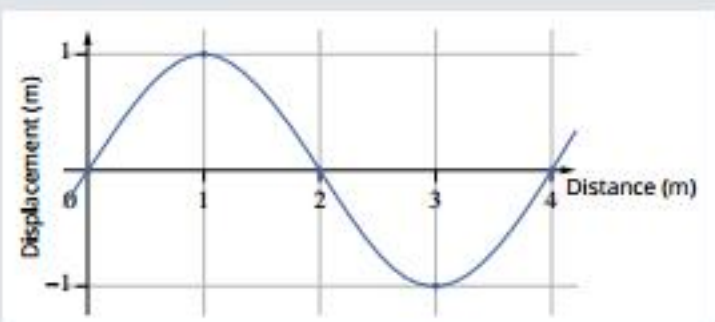
A 6×10^{12} Hz

B 6×10^{14} Hz

C 6×10^{15} Hz

D 6×10^{16} Hz

7 The wave shown below has a frequency of 540Hz. What is its speed?



A $2160\,ms^{-1}$

B $1080\,ms^{-1}$

C $540\,ms^{-1}$

D $135\,ms^{-1}$

8 Cem observes a travelling wave with a wavelength λ. Two points along the wave vibrate with a phase difference of 180°. What is the shortest possible distance between these two points?

A $\frac{\lambda}{4}$

B $\frac{\lambda}{2}$

C λ

D 2λ

9 A sound wave has a wavelength of 1.2 m and a frequency of 283 Hz. What is the nature of the wave and what is the distance the wave travels in 5.0 ms?

	Nature of the wave	Distance travelled in 5.0 ms (m)
A	longitudinal	1.2
B	transverse	1.2
C	longitudinal	1.7
D	transverse	1.7

10 Green light of frequency 5.66×10^{14} Hz is incident on a narrow slit. Determine the slit width in mm that is required for the green light to diffract. The speed of light in air is approximately $3.00 \times 10^{8}\,m\,s^{-1}$.

A 0.00100 mm
B 0.00530 mm
C 0.000100 mm
D 0.000530 mm

11 Duncan observes a standing wave in a pipe with the longest possible wavelength supported by that pipe. Duncan changes the speed of the wave. What can be said about the wavelength and frequency of this wave when the speed is increased?

	Wavelength	Frequency
A	unchanged	increased
B	increased	unchanged
C	unchanged	unchanged
D	increased	increased

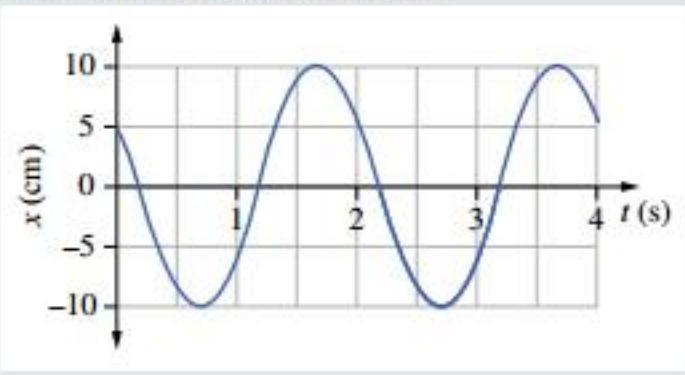
12 State and describe the similarities and differences between a transverse and a longitudinal wave.

13 Classify each of the waves listed below as either a transverse wave or longitudinal wave:
light waves, sound waves, seismic P-waves, seismic S-waves, vibration of a stringed instrument, ripples in a pond, tsunami waves.

14 **a** Draw a transverse wave and label a crest, trough, amplitude and wavelength.
b Draw a longitudinal wave and label a compression, rarefaction and wavelength.

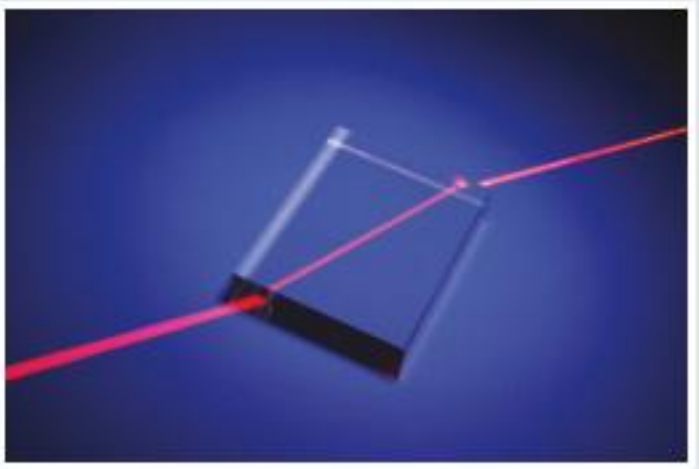
15 When sunlight shines on a house window, its energy can be transmitted, reflected or absorbed. Show the connection between each process and a statement below.
a The room inside the house is illuminated.
b You can see some of the sunlight from outside the house.
c The window glass would start to warm up.

16 The displacement–time graph below shows the variation of the displacement of a specific point on a wave with time.
Identify which of the following wave characteristics can be determined from this type of graph, and state the value of each characteristic: amplitude, frequency, period, wavelength, wave speed.

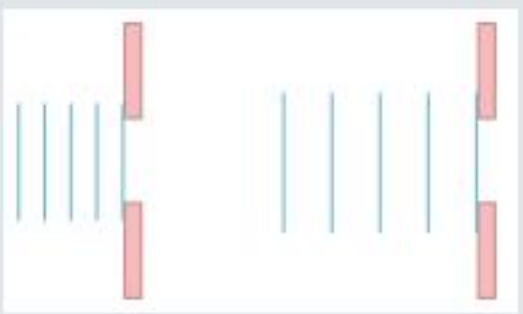


17 A person is standing in front of a mirror combing their hair. They notice that the image they are looking at is the same distance behind the mirror as they are in front of the mirror. Explain the position of the apparent image, called the apparent position, using the wave model of light.

18 In the diagram shown, a light ray is travelling from medium 1 (air) into medium 2 (the glass prism). The light ray can be seen to change direction. Discuss why the light ray changes direction when it passes into medium 2.

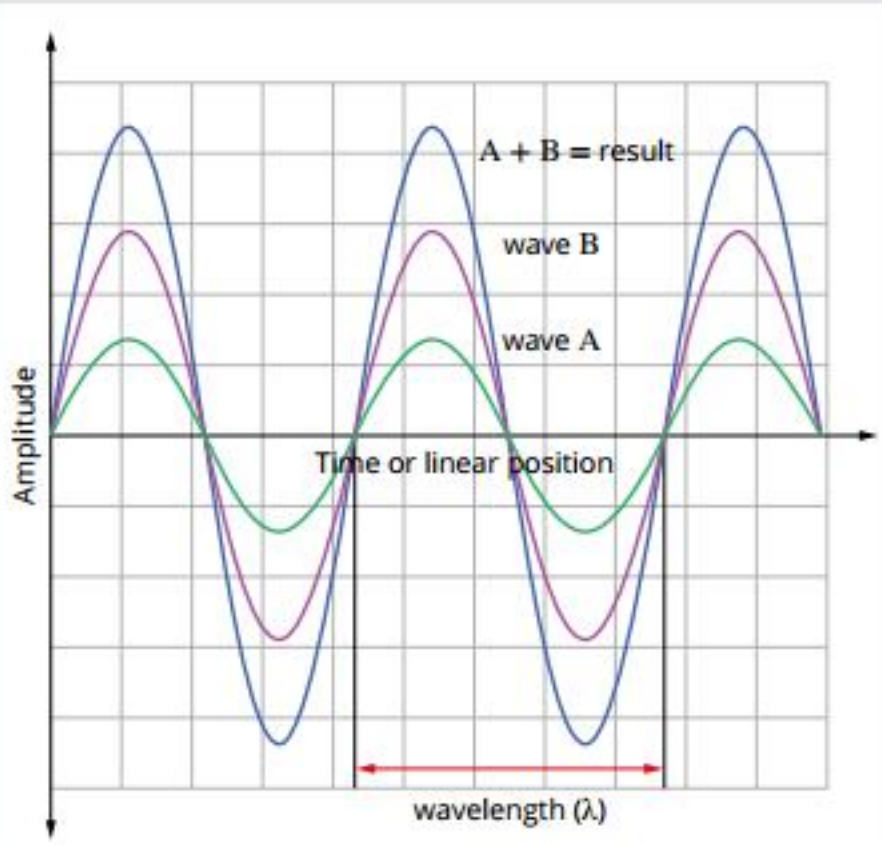


19 In each of the two diagrams below, wavefronts are travelling towards a slit of a particular width. Draw the diffraction wave pattern after the waves have passed through the slits.



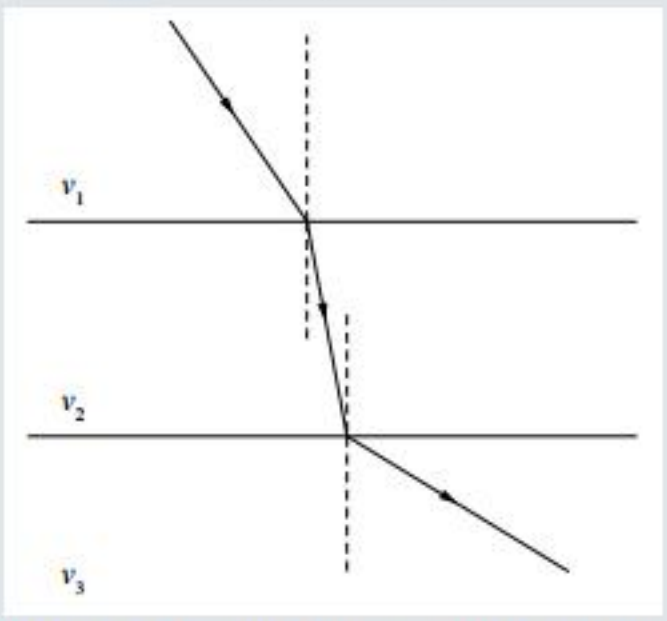
20 The diagram below shows the amplitude of wave A and wave B at a particular time (or linear position). The resultant wave pattern shows the combination of waves A + B. Name the principle and comment on the type of interference pattern this shows.

If one of the waves (A or B) is shifted 180° right or left, explain what would happen to the resultant wave pattern, and describe the type of interference pattern produced.



Analyse

21 A ray of red light is incident on parallel boundaries between 3 different media. The speed of light in each media is v_1, v_2 and v_3 respectively.



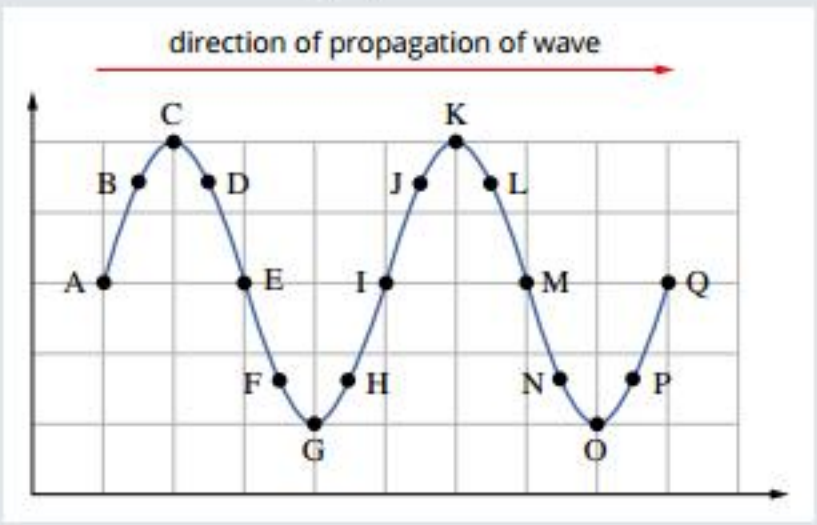
What can be said about the speed of light in the three media?

A $v_1 > v_2 > v_3$
B $v_3 > v_2 > v_1$
C $v_2 > v_1 > v_3$
D $v_2 > v_3 > v_1$

22 On a standing wave, the distance between the first and fifth antinode is 80 cm. What is the wavelength of the wave?

A 16 cm
B 20 cm
C 32 cm
D 40 cm

23 A transverse wave is moving from the left to the right of the page. Determine the directions in which the particles B, D, F and K are moving at the moment in time shown on the graph.

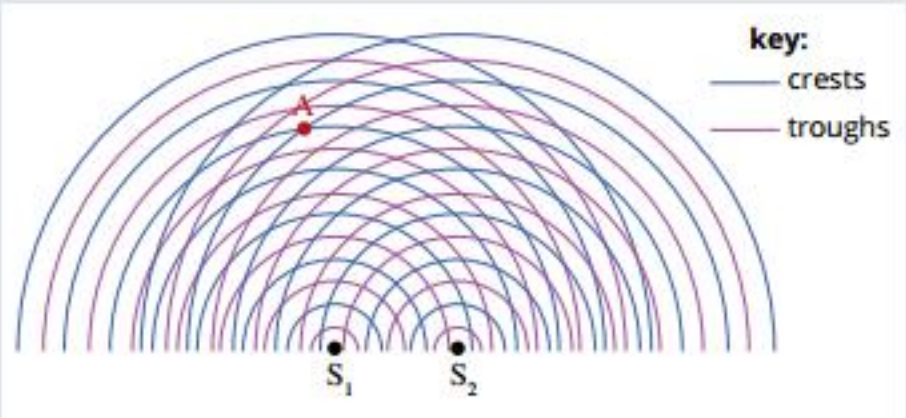


24 A mechanical wave vibrator attached to a string operates at a frequency of 50.0 Hz. If the wave crests formed on the string are 5.0 cm apart, determine the speed of the waves in the string (in $m\,s^{-1}$).

25 Assume the speed of sound in water is approximately $1500\,m\,s^{-1}$ and the speed of sound in air is $340\,m\,s^{-1}$. If the frequency of a sound wave is 350 Hz, calculate the wavelength of this sound wave when it is transmitted in:

a water
b air.

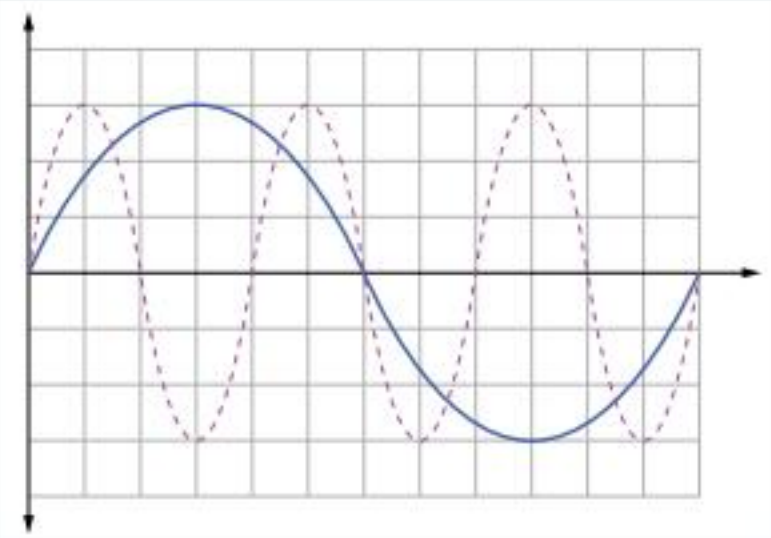
26 Two sources S_1 and S_2 are producing waves in phase with identical wavelengths. The wavefronts of both sources are shown, and a key is provided for the crests and the troughs. The diagram shows a position marked in red and labelled A. Position A is a certain number of wavelengths from both sources. Determine whether destructive or constructive interference occurs between the two sources at the position A. Show all working.



27 Waves are emitted from two sources, 180° out of phase with a wavelength of 40 cm. At a point P, the first source is 1.2 m away and the second source is 1.6 m away. What is the path difference and what is observed at point P?

Interpret

28 Two wave patterns are shown in the diagram below. The solid line represents one wave and the dashed line represents the second wave. Use the principle of superposition to draw the resultant wave pattern from a combination of the two waves.



29 Two speakers are mounted on a wall and are separated by 5.0 m. An observer is standing 30.0 m from the wall, directly in front of one of the speakers. Both speakers are driven by the same source, so the sound waves emitted from the speakers are in phase. Assume the speed of sound in air is 340 $m s^{-1}$. Assess whether the observer hears a quiet, loud or intermediate sound, if the speakers are driven at 850 Hz.

CHAPTER

10 Sound

Sound is an important manifestation of waves. Sound waves allow you to speak and hear, to create language and make music. Sound waves are used to investigate objects that you cannot see, using technologies such as ultrasound and radar. The physics of waves allows us to determine the length of a violin string to create a certain note, or the location of keys on wind instruments to create a scale of notes. Acoustics is the science of sound including ultrasound and infrasound.

Syllabus subject matter

Topic 2 • Waves

■ WAVE PROPERTIES

- Describe examples of transverse and longitudinal waves, such as sound, seismic waves and vibrations of stringed instruments. **10.1, 10.2**
- Solve problems involving the wavelength, frequency, period and velocity of a wave using $v = f\lambda$ and $f = \frac{1}{T}$. **10.1, 10.2, 10.3**

■ SOUND

- Describe the concepts of fundamental (or first) harmonic and natural frequency. **10.1, 10.4**
- Solve problems involving standing wave formation in pipes open at both ends, closed at one end, and on stretched strings using $L = n\frac{\lambda}{2}$ and $L = (2n-1)\frac{\lambda}{4}$. **10.2, 10.3**
- Describe the concept of resonance in a mechanical system. **10.4**
- Identify that energy is transferred efficiently in resonating systems. **10.4**

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10.1 Sound waves

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe sound as a longitudinal, mechanical wave
- understand why the speed of sound is different in different materials and at different temperatures
- use the wave equation to solve problems involving the speed of sound and its wavelength and frequency
- recognise that the sounds you hear are superpositions of sounds at different frequencies
- recognise the lowest frequency produced by an object as the natural frequency, the fundamental frequency, or the first harmonic
- describe harmonics as integer multiples of the fundamental frequency of an object

Most of us have seen science fiction movies that include epic space battles, explosions and sounds that can be heard across the galactic battlefield. In reality, sound is a **mechanical wave** that requires a **medium** to propagate through, which means that sound cannot travel across the vast emptiness of the vacuum of space, so space battles would be eerily silent.

MODEL OF A SOUND WAVE

Sound is a mechanical wave. Mechanical waves transfer energy through vibrations in a medium, as seen in Module 9.1. You would usually experience sound moving through air. Sound cannot travel in vacuums and across space because there are no materials to transfer the energy of the sound wave.

Sound waves are modelled as a longitudinal wave with particles vibrating in the same dimension as the energy transfer (Module 9.2). Sound waves create compressions and rarefactions of the air molecules through which the wave travels (Figure 10.1.1). Recall that compressions are where the air molecules will come together, and rarefactions are where the air molecules are spread apart.

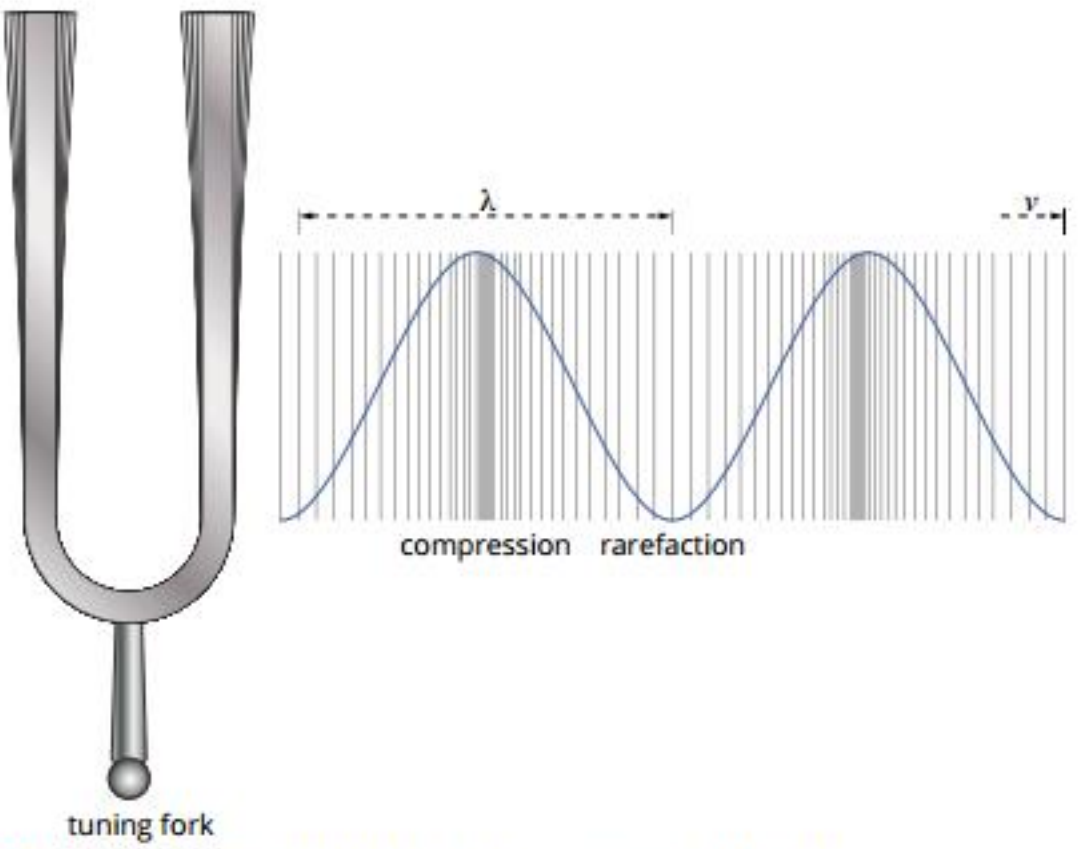


FIGURE 10.1.1 Sound is a longitudinal wave with compressions and rarefactions.

Sound waves are often drawn as transverse waves because the changes in wavelength and frequency are clearly visible, as shown in Figure 10.1.2.

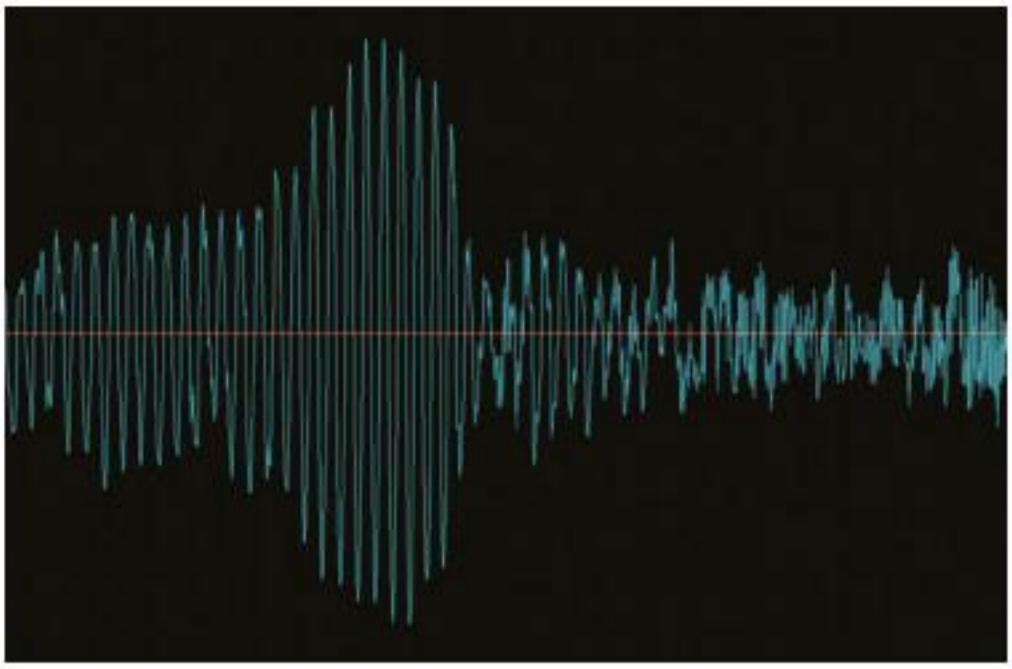


FIGURE 10.1.2 A whale song represented as a transverse wave. Changes in frequency and amplitude are more apparent when waves are represented in a transverse form.

SPEED OF SOUND

Sound is a mechanical wave, so the speed at which the wave travels depends on the material in which the sound wave travels. The stiffer the structure of the material, the faster the sound will travel. This stiffness is the **elastic modulus** of a material.

To understand why the stiffness of a material will affect the speed of sound, consider a model of matter as a series of balls and springs. The balls are the atoms and the springs are the bonds between them. The more spongy a spring, the slower energy travels through the spring; the stiffer the springs, the faster the energy travels through the ball–spring system. As the bonds between atoms become stiffer, the faster sound will travel through a material.

In different states of matter sound also travels at different speeds due to the matter's elastic modulus. Gases and liquids are more spongy than a solid, so will have a lower elastic modulus than a solid and a slower speed of sound. This means solids generally have the fastest speeds of sound, then liquids, then gases. It is easier to transfer energy between atoms in a solid than between the atoms in a gas. To see some examples of this increase in speed see Table 10.1.1.

TABLE 10.1.1 Speed of sound in some common materials

Material	Speed of sound (at 20°C) ($m\,s^{-1}$)
air	343
helium	927
methanol	1143
fat	1450
water	1483
muscle	1580
rubber	1600
gold	3240
bone	4080
iron	5130
Pyrex glass	5640
diamond	12000

FIGURE 10.1.3 An ultrasound being performed on a patient's hand and wrist

FIGURE 10.1.4 Ultrasonic testing of gas cylinders. The technician is holding a transducer against the side of a cylinder. The transducer passes high-frequency sound waves through the metal and picks up any echoes. This allows the technician to assess the thickness of the cylinder wall and to check for any defects.

To understand the effect of the speed of sound, consider what your voice sounds like if you breathe in some helium or balloon mix. (Be very careful if you try this!) What does your voice sound like? If you breathe in a gas more dense than air, your voice will sound lower.

The speed of sound in a material is also temperature dependent, as the temperature can affect the stiffness or elastic modulus of a material, especially for a gas. The temperature increase raises the stiffness of a material, increasing the speed of sound. Therefore, as temperature increases, so does the speed of sound. Some examples of this temperature dependency can be seen in Table 10.1.2.

TABLE 10.1.2 Speed of sound in air and water at different temperatures. Note: $T_K = T_C + 273$

Material	Temperature (K)	Speed of sound ($m s^{-1}$)
air	233	306
air	273	331
air	293	343
air	313	355
water	273	1403
water	293	1483
water	313	1526

These properties of sound mean it can be used in ultrasonic imaging and testing. For example, sound waves travel at different speeds through different body tissues, so ultrasound is often used to see inside the human body (Figure 10.1.3). Ultrasound can also be used to see inside machinery, to measure thicknesses and to detect faults in equipment (Figure 10.1.4).

In summary, the speed of sound in a material depends on the elasticity and the temperature of the material.

- The stiffer the material, the faster the speed of sound in the material.
- The higher the temperature of the medium, the faster the speed of sound in the material.

Working with the speed of sound

The speed of sound waves can be linked with the frequency and wavelength of sound using the wave equation, allowing for the determination of the frequency or wavelength of the sound. Recall the wave equation from Chapter 9, which gives the relationship between frequency, f (Hz), speed, v ($m s^{-1}$), and wavelength, λ (m).

$$v = f\lambda$$

Worked example 10.1.1

REVISITING THE WAVE EQUATION

A sound wave is travelling through water at 293 K. The sound wave has a frequency of 620 Hz. Calculate the wavelength, λ, of the sound wave.

Thinking	Working
Find the speed of sound in water at 293 K in Table 10.1.2: $v = 1483\ m s^{-1}$. As both v and f are known, the wavelength, λ, can be found. Rewrite the wave equation in terms of λ.	$v = f\lambda$ $\lambda = \frac{v}{f}$
Substitute the known values and solve.	$\lambda = \frac{1483}{620}$ $= 2.4\ m$

➤ Try yourself 10.1.1

REVISITING THE WAVE EQUATION

A sound wave is travelling through helium at 20.0 °C and has a wavelength of 0.760 m. Calculate the frequency of the sound wave.

HARMONICS

Most sounds you hear are not just one frequency of sound. Sounds are often a combination of different frequencies, which are called **harmonics** (Module 9.6). These sound waves undergo superposition to create the sound waves that you hear. Sound waves have different combinations of frequencies—this is why you can distinguish the sounds of different musical instruments. To separate these frequencies, the waves can be analysed using a mathematical technique known as a fast Fourier transform. This will show what frequencies have been combined to make the wave. Fast Fourier transforms can be performed on many data logging interfaces (Figure 10.1.5).

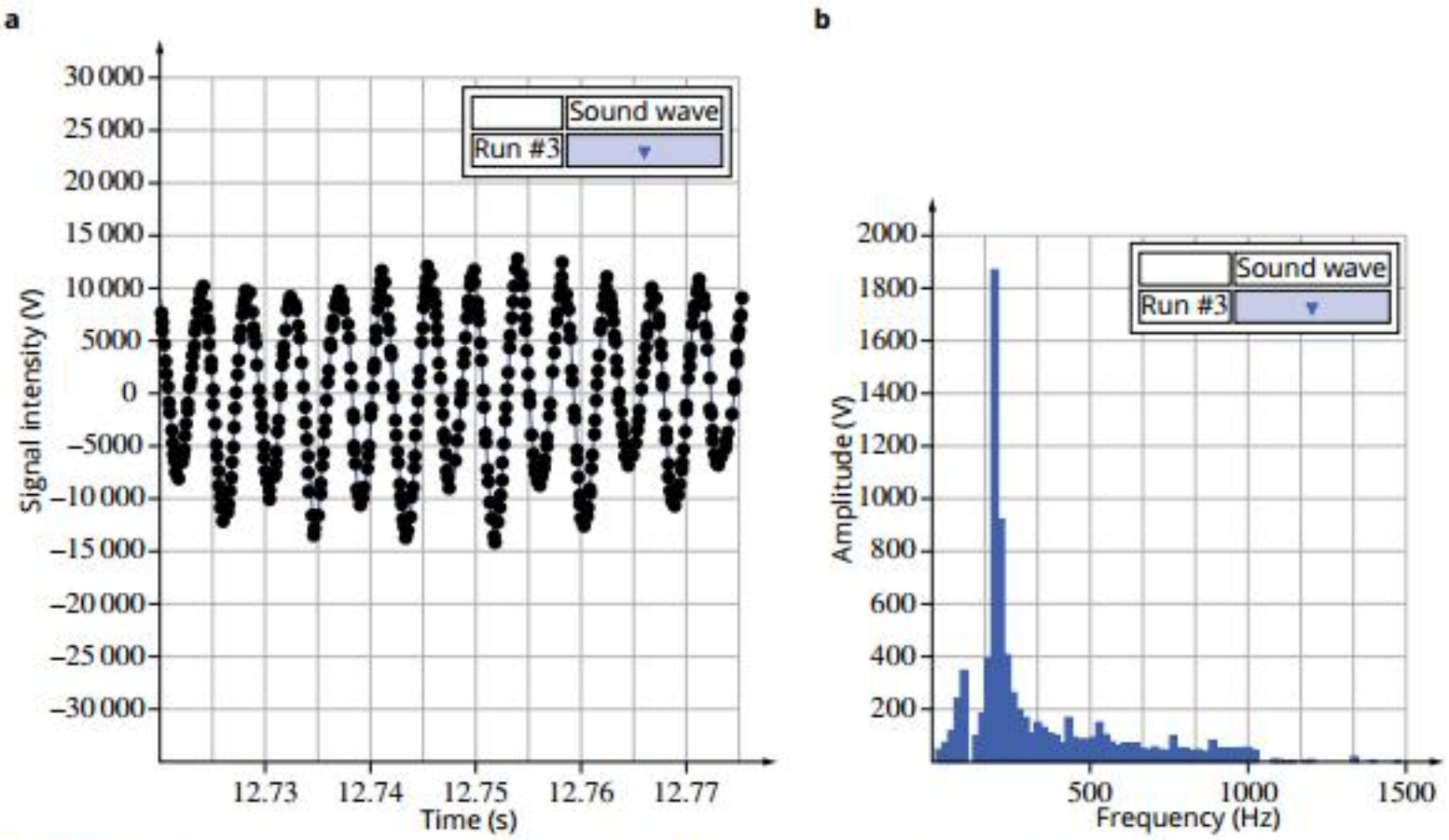


FIGURE 10.1.5 (a) A sound wave from a guitar (b) The fast Fourier transforms of that sound wave showing what frequencies were combined to make that sound

When producing sounds, many instruments create different harmonics (which will be explored in the following modules). The smallest or lowest of the frequencies for a given length of string or pipe is called the **fundamental** frequency or the **first harmonic**. The next frequency produced will be the second frequency or second harmonic, then the third frequency or the third harmonic and so on. Each of these frequencies produced is an integer (whole number) multiple of the fundamental frequency.

10.1 Review

SUMMARY

- Sound waves are mechanical waves that require a medium to travel through.
- Sound waves are longitudinal waves.
- The speed of a sound wave depends on the medium the wave is travelling through and its temperature.
- The higher the temperature of a material, the faster sound can propagate through the material.
- The stiffer the material, the faster sound can propagate through it.
- Sounds often consist of a superposition of many sound waves of different frequencies.
- The lowest of these frequencies is known as the fundamental frequency, or the first harmonic.
- Harmonics are integer multiples of the fundamental frequency of an object and are named in increasing order (for example, second harmonic, third harmonic).

KEY QUESTIONS

Describe

1 Describe the process of energy transfer in a sound wave.

2 Identify the name of the lowest frequency of an instrument.

3 Describe the relationship between the fundamental frequency of a vibrating object, and all higher harmonic frequencies.

Apply

4 Explain why sound cannot travel across a vacuum.

5 Explain why your voice sounds higher when you breathe in balloon gas, which is mostly helium. Do not try this at home.

6 Describe what would happen to a sound's frequency if the period was doubled.

Analyse

7 A 256 Hz sound is played in air with a wavelength of 1.34 m. Calculate the speed of sound.

8 A sound wave is travelling through iron and has a frequency of 400.0 Hz. Calculate its wavelength.

9 Sound is travelling through air at 343 $m\,s^{-1}$ with a wavelength of 0.78 m. Calculate the period of the sound.

10 Identify the trend between air temperature and speed of sound in Table 10.1.2 on page 388.

10.2 Strings

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the creation of standing waves on a stretched string
- calculate the frequency and wavelength of the fundamental frequency and the harmonics generated by a stretched string fixed at both ends.
- calculate the frequency and wavelength of the fundamental frequency and the harmonics generated by a stretched string fixed at one end.

Drawing a bow across a violin string causes the string to vibrate between the fixed bridge of the violin and the finger of the violinist (Figure 10.2.1). The simplest vibration will have maximum amplitude at the centre of the string, halfway between the bridge and the finger. This is a very simple example of a transverse standing wave.

FIGURE 10.2.1 Transverse standing waves can form along a violin string when the string is bowed by the violinist.

STANDING WAVES

Recall from Module 9.7 that standing waves are formed from the superposition of waves. They occur when two waves of the same amplitude and frequency are travelling in opposite directions towards each other in the same string. Usually, one wave is the reflection of the other. Standing waves are responsible for the wide variety of sounds associated with speech and music. A wave pulse is reflected back 180° out of phase when it reaches a fixed end, as discussed in Module 9.3. Crests are reflected as troughs and troughs are reflected as crests. For a continuous wave this can produce a standing wave for certain frequencies.

The nodes in a standing wave, where the waves have interfered destructively, are stationary. The antinodes of a standing wave, where the two waves have interfered constructively, also have a stationary point on the string, but they oscillate with the maximum amplitude. Nodes and antinodes in a standing wave remain in a fixed position for a particular frequency of vibration. Figure 10.2.2 illustrates a series of possible standing waves in a rope with both ends fixed, corresponding to three different frequencies. The distance between nodes is one-half of a wavelength. Assume that the tension in the rope is kept the same in all three standing waves.

- Figure 10.2.2a shows the lowest frequency of vibration, which produces a standing wave with one antinode in the centre of the rope. Note one-half of a wavelength is shown here, so the wavelength, λ, is twice the length of the string.
- Figure 10.2.2b shows waves produced at two times the original frequency. Note that one wavelength is shown here, so the wavelength, λ, is equal to the length of the string.
- Figure 10.2.2c shows waves produced at three times the original frequency. Note that one-and-a-half wavelengths are shown here, so the wavelength, λ, is two-thirds of the length of the string.

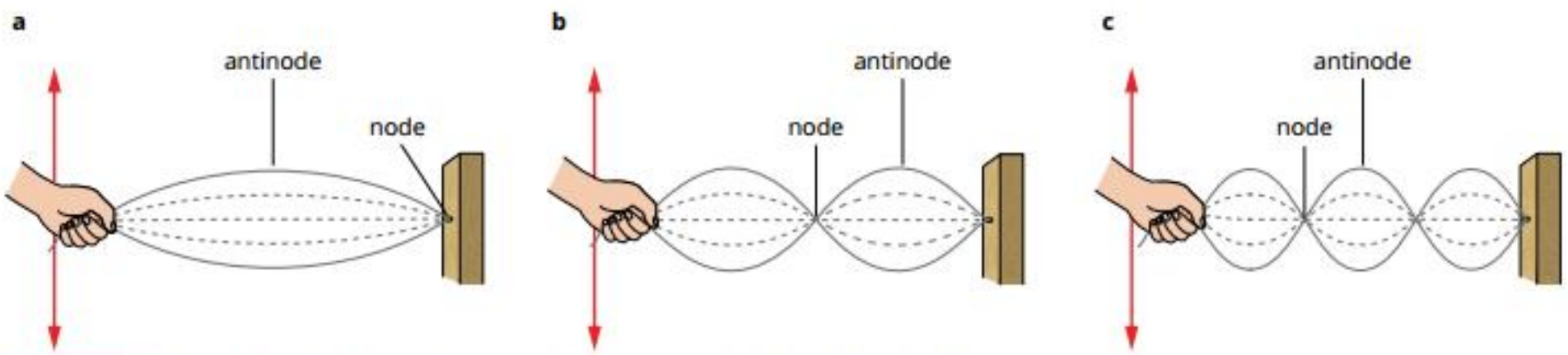


FIGURE 10.2.2 A rope vibrated at three different resonant frequencies, illustrating the standing waves produced at each frequency.

The rope could also vibrate at a frequency four times that of the original and so on. The frequencies at which standing waves are produced are called the resonant frequencies of the rope. It is important to note that the formation of a standing wave does not mean that the string or rope itself is stationary. It will continue to oscillate as further wave pulses travel up and down the rope. It is the relative position of the nodes and antinodes that remain unchanged. It is also important to note that standing waves are not a natural consequence of every wave reflection.

As explained in Module 9.7, standing waves are only produced by the superposition of two waves of equal amplitude and frequency, travelling in opposite directions. Standing waves are a result of resonance and occur only at the natural frequencies of vibration, or resonant frequencies, of the medium. This is discussed in more detail in Module 10.4.

Harmonics and the fundamental frequency

The resonant frequencies produced in the complex vibrations of multiple standing waves are called harmonics. The lowest and simplest form of vibration has one antinode and is called the fundamental frequency (Figure 10.2.2a on page 391). Higher-level harmonics are called the second harmonic (Figure 10.2.2b) and third harmonic (Figure 10.2.2c) and so on.

The fundamental frequency usually has the greatest amplitude, so it has the greatest influence on the sound. The amplitude generally decreases for each subsequent harmonic. Usually, all possible harmonics are produced in a string simultaneously, and the instrument and the air around it also vibrate to create the complex mixture of frequencies, which are heard as an instrumental note.

STRING FIXED AT BOTH ENDS

Instruments in the string family, in their most basic form, consist of a set of tensioned strings of different densities, fixed at both ends. The string family includes instruments such as the violin, viola, cello, double bass, guitar, ukulele, harp, zither and piano. A selection of some string instruments can be seen in Figure 10.2.3. The instruments are plucked, bowed or struck to create vibrations in the form of standing waves in the strings. A standing wave, with the help of resonance with the body of the instrument, transfers this wave energy to the air, through which it travels to our ears for us to enjoy. Figure 10.2.4 is an example of a standing wave on a string.

FIGURE 10.2.3 A selection of string instruments. From the left, a violin, viola, cello and a double bass.

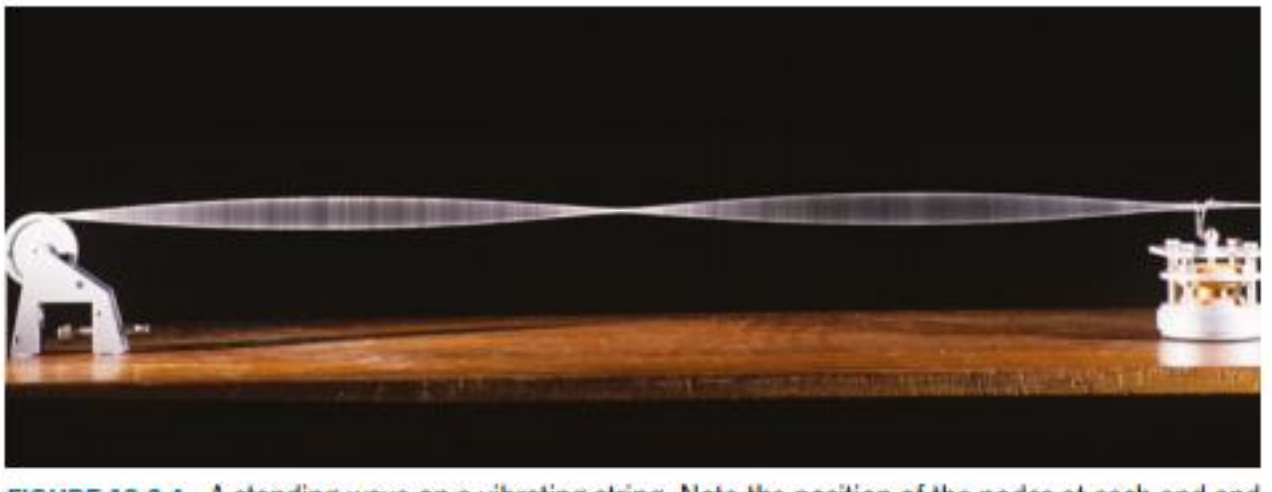


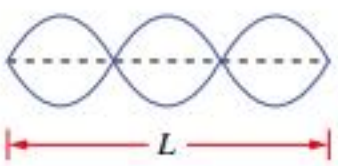
FIGURE 10.2.4 A standing wave on a vibrating string. Note the position of the nodes at each end and in the middle, with the antinodes in between the nodes. You can observe this in the laboratory using a standing wave generator.

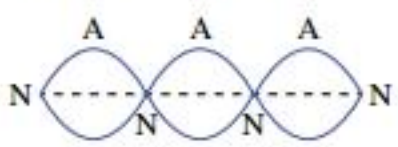
A standing wave, and its pattern of nodes and antinodes, in a string fixed at both ends is examined in Worked example 10.2.1.

Worked example 10.2.1

STANDING WAVES

A standing wave pattern in a string fixed at both ends to a wall is shown in the diagram. The distance between the two fixed points on the wall is a length L.

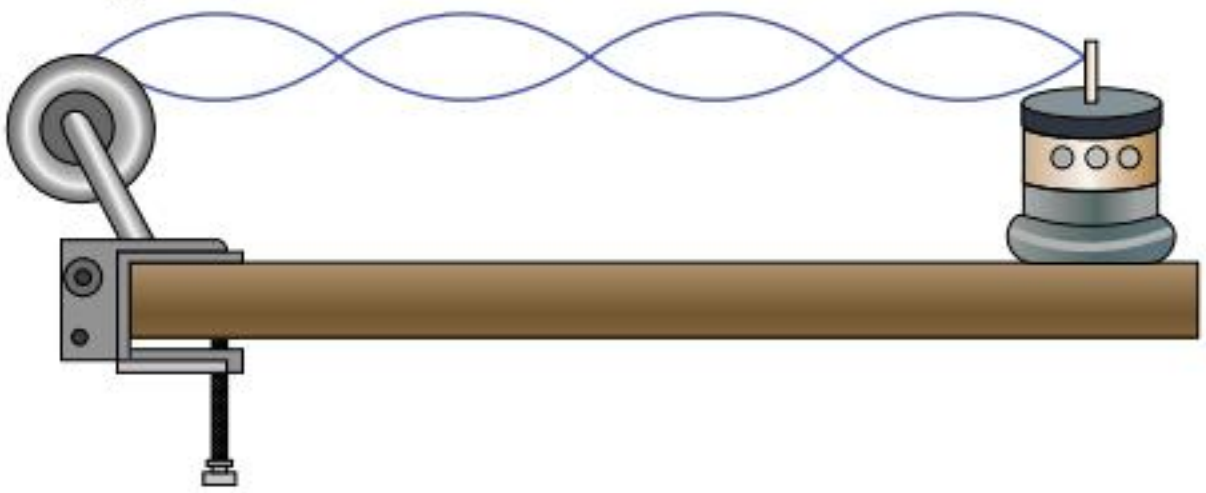


Thinking	Working
a Determine how many nodes and antinodes there are in the standing wave pattern.	
Nodes, N, are points of zero displacement. Antinodes, A, are points of maximum displacement.	This standing wave pattern has four nodes and three antinodes. 
b State the relationship between the length, L, and the wavelength, λ, for this standing wave.	
The distance between nodes is one-half of a wavelength. This standing wave diagram has three antinodes and four nodes. This corresponds to three one-half wavelengths.	$L = 3 \times \frac{\lambda}{2}$ or $\lambda = \frac{2L}{3}$

➤ Try yourself 10.2.1

STANDING WAVES

In the figure below, a mechanical wave generator attached to a lightweight string is vibrating and producing standing wave patterns in the string. The distance between the wave generator and the other end is 1.0 m. Label the nodes N and the antinodes A for this standing wave pattern, state the relationship between the length, L, and the wavelength, λ, and then find the wavelength of the standing wave pattern.



A variety of waves can be created from the strings of a musical instrument. The waves travel along the string in both directions and reflect from the fixed ends. Most of these vibrations will interfere in a random fashion and die away. However, those corresponding to resonant frequencies of the string will form standing waves and remain.

In a musical instrument with a string fixed at both ends, the resonant frequencies or harmonics can be calculated from the relationship between the length of the string, L, and the wavelength, λ, in a standing wave.

The first harmonic, or fundamental frequency, has one antinode in the centre of the string:

$$\lambda = \frac{2L}{1} = 2L$$

The second harmonic will have two antinodes:

$$\lambda = \frac{2L}{2} = 2L$$

The third harmonic will have three antinodes:

$$\lambda = \frac{2L}{3}$$

And so, in general, for any harmonic:

$$\lambda = \frac{2L}{n} = 2L \quad \text{and} \quad L = n\frac{\lambda}{2}$$

The relationship between wavelength, λ, and string length, L, is shown in Figure 10.2.5.

For a string fixed at both ends:

$$L = n\frac{\lambda}{2}$$

where

L is the length of the string (m)

λ is the wavelength (m)

n is the number of the harmonic, which is also the number of antinodes (1, 2, 3, 4, ...).

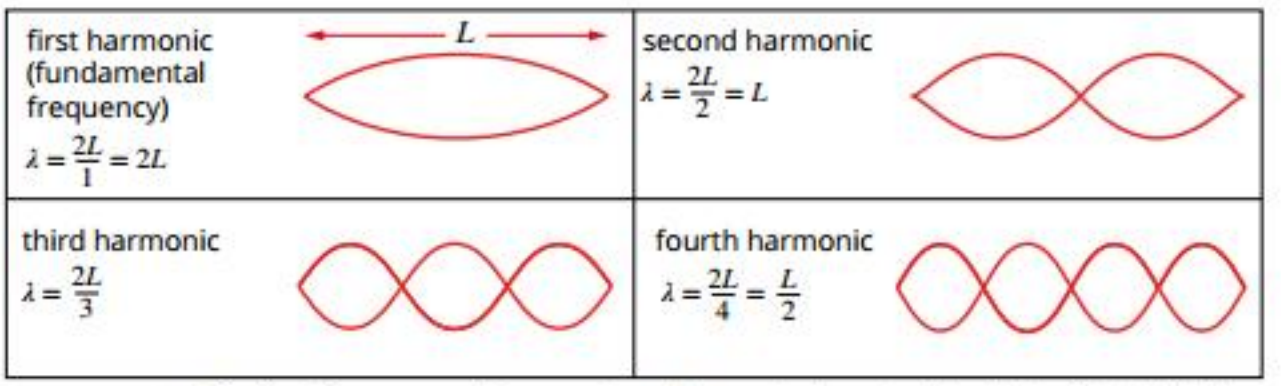


FIGURE 10.2.5 The first four resonant frequencies, or harmonics, in a stretched string fixed at both ends. The ends are fixed so they will always be nodal points.

The wave equation $v = f\lambda$ gives the relationship between frequency, speed and string length.

For the first harmonic, or fundamental frequency ($\lambda = 2L$):

$$v = f\lambda \text{ and so } f = \frac{v}{\lambda} = \frac{v}{2L}$$

For the second harmonic ($\lambda = L$):

$$f = \frac{v}{\lambda} = \frac{v}{L}$$

For the third harmonic $\left(\lambda = \frac{2L}{3}\right)$:

$$f = \frac{v}{\lambda} = \frac{v}{1} \times \frac{3}{2L} = \frac{3v}{2L}$$

And so, in general, for a string fixed at both ends:

$$f = n\frac{v}{2L}$$

Worked example 10.2.2

FUNDAMENTAL FREQUENCY FOR STRINGS FIXED AT BOTH ENDS

A violin string, fixed at both ends, has a length of 22 cm. It is vibrating at its fundamental frequency of vibration at 880 Hz.

a Determine the wavelength of the fundamental frequency.

Thinking	Working
Identify the length of the string, L, in metres and the harmonic number, n.	$L = 22\,\text{cm} = 0.22\,\text{m}$ $n = 1$
Recall that $L = n\frac{\lambda}{2}$. Rearrange $L = n\frac{\lambda}{2}$ to make λ the subject. Substitute the known values and solve for λ.	$\lambda = \frac{2L}{n}$ $= \frac{2 \times 0.22}{1}$ $= 0.44\,\text{m}$

b Determine the wavelength of the second harmonic.

Thinking	Working
Identify the length of the string, L, in metres and the harmonic number, n.	$L = 22\,\text{cm} = 0.22\,\text{m}$ $n = 2$
Recall that $L = n\frac{\lambda}{2}$. Rearrange $L = n\frac{\lambda}{2}$ to make λ the subject. Substitute the known values and solve for λ.	$L = n\frac{\lambda}{2}$ $\lambda = \frac{2L}{n}$ $= \frac{2 \times 0.22}{2}$ $= 0.22\,\text{m}$

You may see the equations for the wavelength and frequency of waves in a string written with λ as the subject. For example,

$$L = n\frac{\lambda}{2}$$

may be written as

$$\lambda = \frac{2L}{n}$$

By rearranging one of these, you can see that the two forms of the equation are equivalent. Use the form that is most helpful for you in answering questions. You will frequently be asked to find the wavelength or frequency of a wave or harmonic, so you would use an equation with λ or f as the subject.

➤ Try yourself 10.2.2

FUNDAMENTAL FREQUENCY FOR STRINGS FIXED AT BOTH ENDS

A standing wave in a string is found to have a wavelength of 0.50 m for the fundamental frequency of vibration. Assume that the tension of the string is not changed and that the string is fixed at both ends.

a Determine the length of the string.

b Determine the wavelength of the third harmonic.

STRING FIXED AT ONLY ONE END

A flexible string fixed at one end cannot create enough tension for the efficient energy transfer required to create a sound. However, in musical instruments this can be achieved by using stiff materials such as metal. An example of an instrument that functions like a string fixed at only one end is the kalimba or thumb piano (Figure 10.2.6). The stiff metal strings, called tines, are fixed at one end but free to move at the other end. This creates a system of a string with only one fixed end, which makes a sound when plucked.

The standing waves that form in a string with only one fixed end are shown in Figure 10.2.7 on page 396. Note that only odd-numbered harmonics are possible, because only these satisfy the condition of having a node at the fixed end and an antinode at the free end. A node will always form at the fixed end (the left-hand side of Figure 10.2.7) and an antinode will always form at the free end (the right-hand side of Figure 10.2.7) of the string.

FIGURE 10.2.6 A kalimba or African thumb piano. The metal tines are fixed at one end and free to move at the other end as a string with one fixed end.

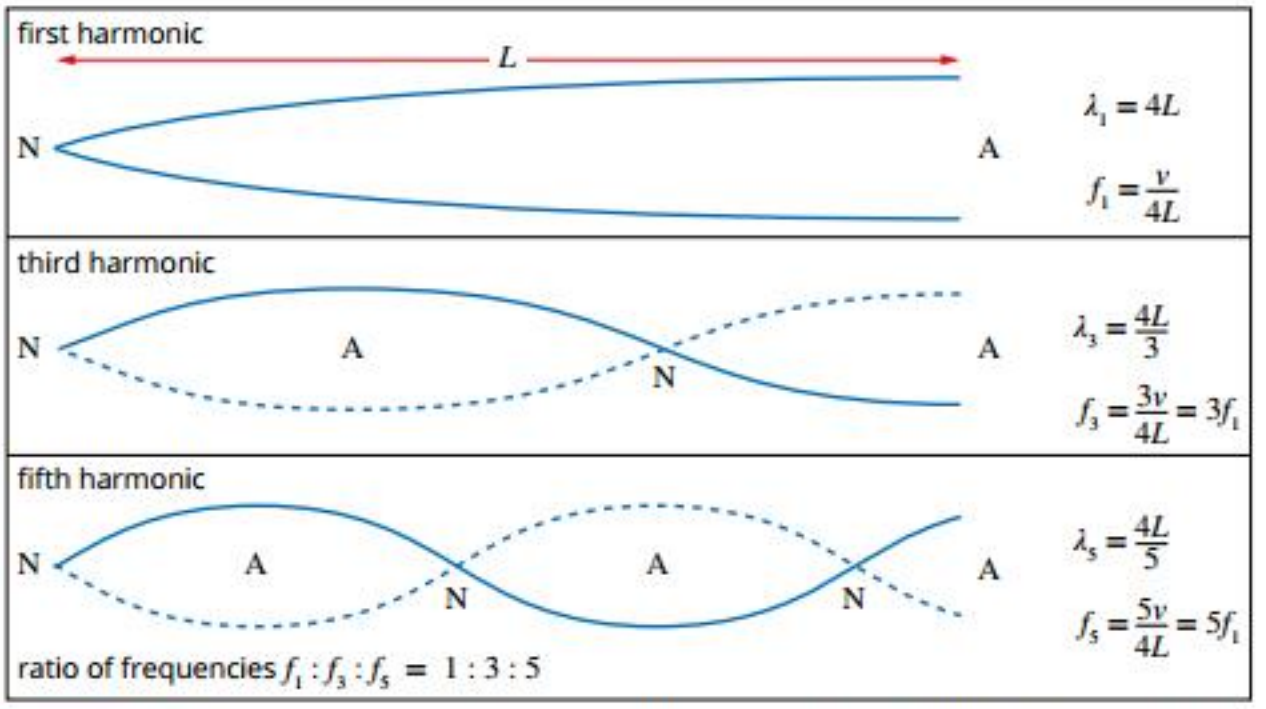


FIGURE 10.2.7 The lower harmonics for a string that is fixed at one end (the left-hand side) and free to move at the other end (the right-hand side).

The first harmonic, or fundamental frequency, will have a wavelength four times the length of the string:

$$\lambda = 4 \times L$$

The next simplest harmonic that can form will have a wavelength:

$$\lambda = \frac{4 \times L}{3}$$

The next harmonic that can form will have a wavelength:

$$\lambda = \frac{4 \times L}{5}$$

And so, in general, for a string fixed at one end:

$$\lambda = \frac{4L}{n} = 2L \quad \text{and} \quad L = n\frac{\lambda}{4}$$

Substituting the wave equation $v = f\lambda$ into the equation for a string fixed at only one end gives the frequency in terms of velocity:

$$\lambda = \frac{4L}{n}$$

$$\frac{v}{f} = \frac{4L}{n}$$

$$f = n\frac{v}{4L}$$

Odd-numbered harmonics (1, 3, 5, ...) form with an antinode at the free end and a node at the fixed end. The ratio of the wavelengths of the harmonics will be 1:3:5 and so on. This means the wavelength of the third harmonic is $\frac{1}{3}$ the length of the fundamental frequency (the first harmonic), the fifth harmonic is $\frac{1}{5}$ the length of the fundamental frequency and so on.

Even-numbered harmonics (2, 4, 6, ...) will not form. The equations for a standing wave on a string fixed at one end can be modified to incorporate this. The modified formula is:

$$L = (2n - 1)\frac{\lambda}{4}$$

Note that for this equation, n is defined slightly differently from that for strings fixed at both ends. For this equation, n is the next harmonic in the sequence, not the harmonic number.

Substituting the wave equation $v = f\lambda$ gives the frequency in terms of length and velocity:

$$f = (2n - 1)\frac{v}{4L}$$

For a string fixed at only one end:

$L = (2n - 1)\frac{\lambda}{4}$

where

L is the length of the string (m)

n is the next harmonic in the sequence, not the harmonic number.

λ is the wavelength (m).

Although it will not be considered in this unit, it should be noted that the resonant frequencies of a string correspond to a particular tension and mass per unit length. Tightening or loosening the string will change the wavelengths and resonant frequencies for that string (the instrument will need tuning by adjusting the tension of the string). Heavier strings of a particular length will have different resonant frequencies than lighter strings of the same length and tension.

Worked example 10.2.3

FUNDAMENTAL FREQUENCY FOR STRINGS FIXED AT ONE END

A thumb piano is a musical instrument from Africa. It consists of a wooden board with several metal tines attached, which are struck with the thumb to make a sound. It can be modelled as a string with one fixed end.

A thumb piano tine, fixed at one end, has a length of 5.0 cm.

a Calculate the wavelength of the fundamental frequency.

Thinking	Working
Identify the length of the string, L, in metres and the harmonic number, n.	$L = 5.0\,\text{cm} = 0.05\,\text{m}$ $n = 1$
Recall that for any frequency, for a string fixed at only one end $L = (2n-1)\frac{\lambda}{4}$. Rearrange the equation to make λ the subject. Substitute the values from the question and solve for λ.	$L = (2n-1)\frac{\lambda}{4}$ $\lambda = \frac{4L}{(2n-1)}$ $= \frac{4 \times 0.05}{(2 \times 1 - 1)}$ $= 0.20\ \text{m}$

b Calculate the wavelength of the third harmonic.

Thinking	Working
Identify the length of the string, L, in metres and the harmonic number, n. Recall that for a string fixed at one end, the third harmonic is the second harmonic in the sequence.	$L = 5.0\,\text{cm} = 0.05\,\text{m}$ $n = 2$
Recall that for any frequency, for a string fixed at only one end $L = (2n-1)\frac{\lambda}{4}$. Rearrange the equation to make λ the subject. Substitute the values from the question and solve for λ.	$L = (2n-1)\frac{\lambda}{4}$ $\lambda = \frac{4L}{(2n-1)}$ $= \frac{4 \times 0.05}{(2 \times 2 - 1)}$ $= 0.067\,\text{m}$

➤ Try yourself 10.2.3

FUNDAMENTAL FREQUENCY FOR STRINGS FIXED AT ONE END

A standing wave in a tine on a thumb piano is found to have a wavelength of 0.080 m for the fundamental frequency of vibration.

a Determine the length of the tine.

b Determine the wavelength of the fifth harmonic.

The discussion in this section has only included two-dimensional standing waves, but standing waves may also form in three dimensions, such as in a section of the Earth's crust during an earthquake. Standing waves will form as a result of resonance in any waveform.

10.2 Review

SUMMARY

- Standing or stationary waves occur at the natural frequency of vibration.
- Points on a standing wave that remain still are called nodes.
- Points of maximum amplitude on a standing wave are called antinodes.
- The standing wave frequencies are referred to as harmonics. The simplest frequency is referred to as the fundamental frequency.
- In a string fixed at both ends, the relationship between string length and wavelength is:

$$L = n\frac{\lambda}{2}$$

This equation can be combined with the general wave equation $v = f\lambda$ to give a relationship between frequency, speed, and length:

$$f = n\frac{v}{2L}$$

All harmonics may be present.

- In a string fixed at only one end, the relationship between string length and wavelength is:

$$L = (2n - 1)\frac{\lambda}{4}$$

This equation can be combined with the general wave equation $v = f\lambda$ to give a relationship between frequency, speed, and length:

$$f = (2n - 1)\frac{v}{4L}$$

For the equations for a string fixed at only one end, n is the next harmonic in the sequence, not the harmonic number.

KEY QUESTIONS

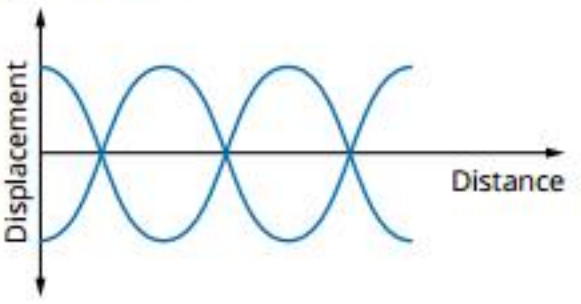
Describe

1 Is the wave shown below the first harmonic or the second harmonic?

Apply

2 A standing wave is produced in a rope fixed at one end by vibrating the rope with five times the frequency that produces the fundamental or first harmonic. Discuss how much larger or smaller the wavelength of this standing wave is compared to that of the fundamental or first harmonic.

3 A standing wave pattern is shown below. Determine if it is possible to produce this standing wave pattern on a stringed instrument.



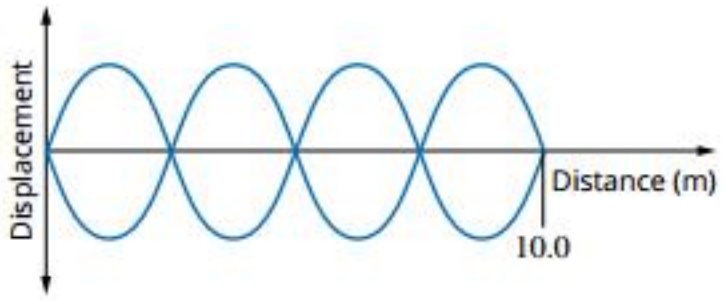
Analyse

4 Calculate the length of a string fixed at both ends when the wavelength of the fourth harmonic is 0.75 m.

5 Calculate the wavelength of the fundamental frequency of a standing wave on a string 0.40 m long and fixed at one end.

6 Calculate the frequency of the second harmonic produced by a 650 mm long guitar string vibrating in air at 20°C.

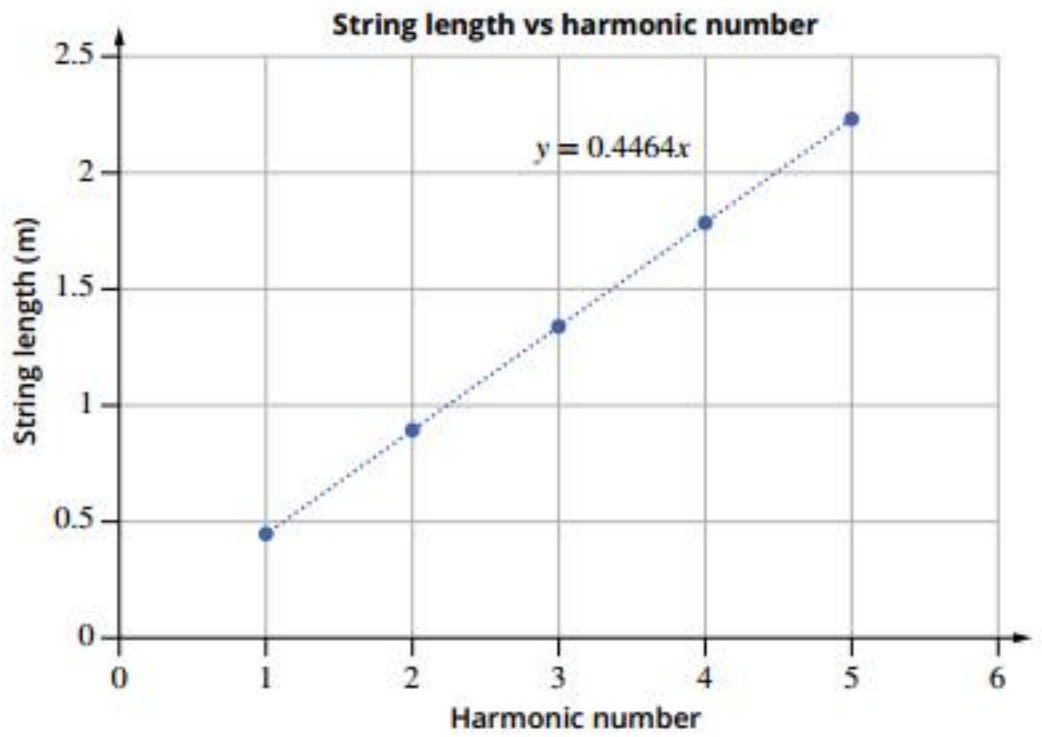
7 The diagram below shows a standing wave pattern in a string over 10.0 m. Calculate the length of the string that would generate the first harmonic of a standing wave of the same wavelength as shown.



8 The fundamental frequency of a violin string is 350 Hz and the velocity of the waves along it is 387 m s^{-1}. Calculate the wavelength of the new fundamental frequency when a finger is pressed to shorten the string to $\frac{2}{3}$ its original length.

*The following information relates to questions **9 and 10**.*

A student has conducted an experiment to determine the speed of sound using a string. They do so by oscillating the string continuously at a frequency of 392 Hz and varying the length of the string to achieve different harmonics. The data from the experiment is shown on the graph below.



9 Analyse the graph to determine the speed of sound recorded for this experiment.

10 Evaluate the accuracy of the experiment given it was conducted at a temperature of 25°C where $v = 346\,\text{m s}^{-1}$.

10.3 Pipes

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the creation of standing waves in a pipe
- calculate the frequency and wavelength of the fundamental frequency and the harmonics generated by a pipe with both ends open
- calculate the frequency and wavelength of the fundamental frequency and the harmonics generated by a pipe with one open end and one closed end.

In Module 9.7, you learnt that longitudinal stationary waves are also possible in air columns. These create the sounds associated with wind instruments. Blowing over the hole of a flute (Figure 10.3.1) or the reed of a saxophone (Figure 10.3.2) produces vibrations that correspond to a range of frequencies that create sound waves in the pipe.

The compressions and rarefactions of the sound waves, confined within the tube, reflect from both open and closed ends. This creates the right conditions for resonance and the formation of standing waves. The length of the pipe will determine the frequency of the sounds that will resonate.

The open end of a pipe corresponds to the fixed end of a string in that the reflected wave is fully inverted (it undergoes a 180° change of phase). At a closed end there is no change of phase. The reflected wave is in phase with the original wave.

FIGURE 10.3.2 Blowing into the mouthpiece of a saxophone vibrates the reed that is attached to the mouthpiece, which creates a vibration in the air column. Using the keys to control the length of the saxophone produces particular notes.

FIGURE 10.3.1 Blowing over the mouthpiece of a flute and controlling the length of the flute with the keys enables a particular note to be produced.

PIPES WITH BOTH ENDS OPEN

A flute is an example of a musical instrument with two open ends. Not only can you control the length of the instrument using the keys but, like many instruments, flutes come in several lengths to provide different length pipes (Figure 10.3.3 on page 401). The flautist blows across the embouchure hole, creating the vibration in the air column. This sets up a standing wave from the mouthpiece to the first open key (hole).

At the open end of a pipe, the wave forms an antinode with the reflected wave fully inverted (undergoes a 180° change of phase). In a pipe with two open ends, an antinode is formed at each end of the pipe.

Like the strings in Module 10.2, a large variety of waves are created in the pipe when a vibration is added to the air column within the pipe. These waves will reflect from the open ends of the pipe, but only the frequency that corresponds to a resonant frequency of the length of the instrument will create standing waves and therefore create the sound you hear. These standing waves are (like strings) termed harmonics and add in superposition, with the resultant sound being a combination of a series of harmonics.

In a wind instrument, it is not always the fundamental frequency that dominates the sound heard. The control of the flow of air from a player's mouth to the instrument can often determine which harmonic has the greatest amplitude. These harmonics correspond to octaves to a musician.

The resonant frequencies or harmonics in a pipe of length L can be calculated in the same way that harmonics were calculated for a string with two fixed ends.

The first harmonic, or fundamental frequency, has two antinodes, one at each end of the pipe, and a node in the centre of the pipe and will have wavelength

$$\lambda = \frac{2L}{1} = 2L$$

The second harmonic will have two nodes and will have wavelength

$$\lambda = \frac{2L}{2} = L$$

The third harmonic will have three nodes and will have wavelength

$$\lambda = \frac{2L}{3}$$

And so, in general, for any harmonic:

$$\lambda = \frac{2L}{n} \quad \text{and} \quad L = n\frac{\lambda}{2}$$

The relationship between wavelength, λ, and pipe length, L, is shown in Figure 10.3.4.

FIGURE 10.3.3 A piccolo and flute. A piccolo is a small flute that produces sounds higher (higher frequency) than a flute due to its shorter length.

For a pipe with two open ends:

$$L = n\frac{\lambda}{2}$$

where

λ is the wavelength (m)

L is the length of the pipe (m)

n is the number of the harmonic, which is also the number of nodes (1, 2, 3, 4, ...).

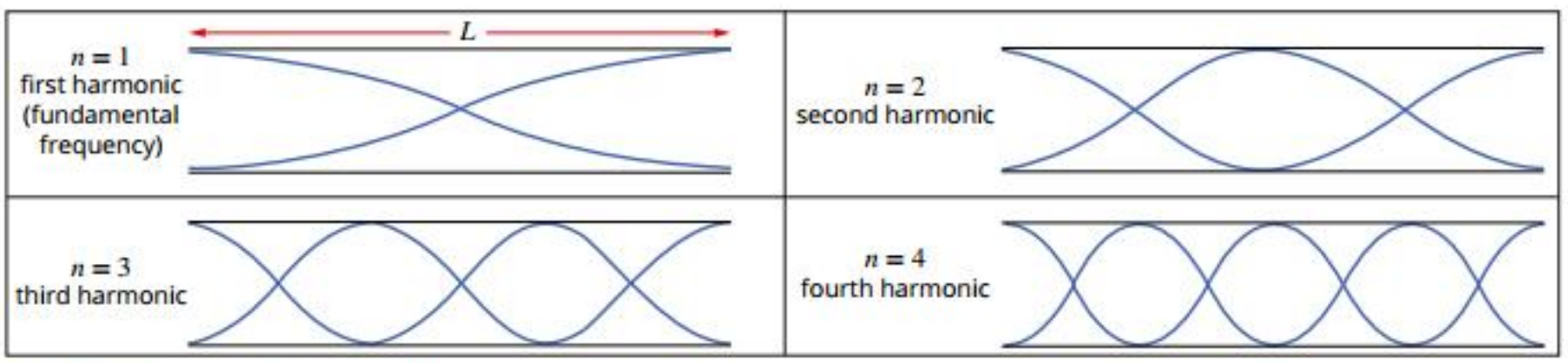


FIGURE 10.3.4 The first four resonant frequencies, or harmonics, in a pipe with two open ends. The ends are open so they will always be antinodal points.

Using the wave equation $v = f\lambda$ gives the relationship between frequency, speed and pipe length.

For the first harmonic, or fundamental frequency ($\lambda = 2L$):

$$v = f\lambda \text{ and so } f = \frac{v}{\lambda} = \frac{v}{2L}$$

For the second harmonic ($\lambda = L$):

$$f = \frac{v}{\lambda} = \frac{v}{L}$$

For the third harmonic $\left(\lambda = \frac{2L}{3}\right)$:

$$f = \frac{v}{\lambda} = \frac{3v}{2L}$$

And so, in general, for a pipe with two open ends:

$$f = n\frac{v}{2L}$$

Worked example 10.3.1

FUNDAMENTAL FREQUENCY FOR PIPES WITH TWO OPEN ENDS

A flute is a 66 cm long pipe with two open ends.

a Calculate the wavelength of the fundamental frequency.

Thinking	Working
Identify the length of the pipe, L, in metres and the harmonic number, n.	$L = 66\,\text{cm} = 0.66\,\text{m}$ $n = 1$
Recall that for any frequency, $L = n\frac{\lambda}{2}$. Rearrange this equation to make λ the subject, then substitute the values from the question and solve for λ.	$L = n\frac{\lambda}{2}$ $\lambda = \frac{2L}{n}$ $= \frac{2 \times 0.66}{1}$ $= 1.3\,\text{m}$

b Calculate the wavelength of the second harmonic.

Thinking	Working
Identify the length of the pipe, L, in metres and the harmonic number, n.	$L = 66\,\text{cm} = 0.66\,\text{m}$ $n = 2$
Recall that for any frequency, $L = n\frac{\lambda}{2}$. Rearrange this equation to make λ the subject, then substitute the values from the question and solve for λ.	$L = n\frac{\lambda}{2}$ $\lambda = \frac{2L}{n}$ $= \frac{2 \times 0.66}{2}$ $= 0.66\,\text{m}$

➤ Try yourself 10.3.1

FUNDAMENTAL FREQUENCY FOR PIPES WITH TWO OPEN ENDS

A standing wave in a flute is found to have a wavelength of 0.38 m for the fundamental frequency of vibration. Assume that the flute is a pipe with two open ends.

a Calculate the length of the flute.

b Calculate the wavelength of the fourth harmonic.

PIPE WITH ONE OPEN END AND ONE CLOSED END

Many woodwind and brass instruments are examples of a pipe with one closed end and one open end. This includes instruments such as clarinets, oboes, saxophones, trumpets, trombones and French horns (Figure 10.3.5). The mouthpiece of these instruments acts as a closed end with node and the bell of the instrument (the other end) acts as an open end of a pipe. Recall that the open end of a pipe results in the reflected wave being fully inverted (undergoes a 180° change of phase). In contrast, at a closed end there is no change of phase. The reflected wave is in phase with the original wave.

FIGURE 10.3.5 A variety of instruments that have one closed end and one open end. From the left: a French horn, a clarinet, a bassoon and an oboe.

The closed end of the pipe creates a node, so a pipe with one open end and one closed end has one end as a node and the other as an antinode. This is the same as in the case for a string with one fixed end, and results in the same equations to find lengths and wavelengths, as seen in Module 10.2.

For a pipe with one open end and one closed end:

$$L = n\frac{\lambda}{4}$$

where

L is the length of the pipe (m).

n is the number of the harmonic (1, 3, 5, ...)

λ is the wavelength (m)

In general, for a pipe with one open end and one closed end, the frequency in terms of speed is:

$$f = n\frac{v}{4L}$$

where

f is the frequency of the wave (Hz)

n is the number of the harmonic, which is also the number of nodes (1, 3, 5, ...)

v is the velocity of the wave ($m\,s^{-1}$)

L is the length of the pipe (m).

Odd-numbered harmonics (1, 3, 5, ...) will form because the conditions necessary for a standing wave to form are only met in circumstances where there is an antinode at the open end and a node at the closed end. The ratio of the wavelengths of the harmonics will be 1 : 3 : 5, ... This means that the wavelength of the third harmonic is $\frac{1}{3}$ the length of the fundamental frequency (the first harmonic), the fifth harmonic is $\frac{1}{5}$ the length of the fundamental frequency, and so on.

Even-numbered harmonics (2, 4, 6, ...) will not form. The equations introduced above can be modified to incorporate this. The modified formula for a pipe with one open end and one closed end is:

$$L = (2n - 1)\frac{\lambda}{4}$$

where

L is the length of the pipe (m)

n is an integer (1, 2, 3, 4, ...).

λ is the wavelength (m)

Note that for this equation, n is defined slightly differently from that for pipes open at both ends. For this equation, n is the next harmonic in the sequence, not the harmonic number.

Worked example 10.3.2

FUNDAMENTAL FREQUENCY FOR PIPES WITH AN OPEN AND A CLOSED END

A clarinet is an example of a pipe with an open and a closed end. The length of the bass clarinet is 101.6 cm.

a Calculate the wavelength of the fundamental frequency.

Thinking	Working
Identify the length of the pipe, L, in metres and the harmonic number, n.	$L = 101.6\,\text{cm} = 1.016\,\text{m}$ $n = 1$
Recall that for any frequency, $L = (2n - 1)\frac{\lambda}{4}$. Rearrange this equation to make λ the subject, then substitute the values from the question and solve for λ.	$L = (2n-1)\frac{\lambda}{4}$ $\lambda = \frac{4L}{(2n-1)}$ $= \frac{4 \times 1.016}{1}$ $= 4.064\,\text{m}$

b Calculate the frequency of the third harmonic. (Use the speed of sound as $343\,\text{m s}^{-1}$.)

Thinking	Working
Identify the length of the pipe, L, in metres, the harmonic number, n, and the speed of the wave, v. Recall that for a pipe with a closed end, the third harmonic is the second harmonic in the sequence.	$L = 1.016\,\text{m}$ $n = 2$ $v = 343\,\text{m s}^{-1}$
Recall that $L = (2n - 1)\frac{\lambda}{4}$ and $v = f\lambda$. Substitute and transpose for f. Substitute the values from the question and solve for f.	$L = (2n-1)\frac{\lambda}{4}$ and $v = f\lambda$ $f = (2n-1)\frac{v}{4L}$ $= (2 \times 2 - 1)\frac{343}{4 \times 1.016}$ $= 253\,\text{Hz}$

➤ Try yourself 10.3.2

FUNDAMENTAL FREQUENCY FOR PIPES WITH AN OPEN AND A CLOSED END

A trombone is a pipe with an open end and a closed end. The fundamental frequency of a trombone is 31 Hz. (Use the speed of sound as $343\,\text{m s}^{-1}$.)

a Calculate the total length of the pipe of the trombone.

b Calculate the wavelength of the third harmonic.

10.3 Review

SUMMARY

- In a pipe with two open ends, the relationship between pipe length and wavelength is:

$$L = n\frac{\lambda}{2}$$

This equation can be combined with the general wave equation $v = f\lambda$ to give the relationship between frequency, speed, and length:

$$f = n\frac{v}{2L}$$

All harmonics may be present.

- In a pipe closed at one end, the relationship between pipe length and wavelength is:

$$L = (2n-1)\frac{\lambda}{4}$$

- This equation can be combined with the general wave equation $v = f\lambda$ to give the relationship between frequency, speed, and length:

$$f = (2n-1)\frac{v}{4L}$$

For the equations for a pipe closed at one end, n is the next harmonic in the sequence, not the harmonic number.

KEY QUESTIONS

Describe

1 Describe the phase of a wave that is reflected at the end of a closed pipe.

2 Describe the harmonics that can form in a pipe with a closed end.

Apply

3 Draw the fundamental frequency and the second harmonic for a wave in a pipe with two open ends.

4 Explain why the sound of water being poured into a glass changes as the glass fills.

Analyse

5 A clarinet (a pipe with one closed end) plays a note at 540 Hz. Assume this is the fundamental frequency. Calculate the effective length of the clarinet, if the speed of sound in the clarinet is 343 $m\,s^{-1}$.

6 Calculate the frequency of the second harmonic for a pipe with two open ends, if the pipe is 47 cm long. (Assume the speed of sound in the pipe is 343 $m\,s^{-1}$.)

7 A pipe with one closed end has a fundamental wavelength of 2.8 m. Calculate the frequency of the third harmonic. (Assume the speed of sound of 343 $m\,s^{-1}$.)

8 A 4.23 m organ pipe with two open ends is played with a speed of sound of 343 $m\,s^{-1}$. Calculate the fundamental frequency and, thus, the period of this note.

9 A wind instrument when played softly emits a 350 Hz note. When played strongly, it emits a 700 Hz note. Determine if the instrument is open at both ends or closed at one end.

10 A plastic children's recorder has an approximate length of 30 cm. Determine how many standing waves can be produced by this instrument with frequencies under 5000 Hz at an air temperature of 25°C (v = 346 $m\,s^{-1}$).

10.4 Resonance and natural frequency

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe resonance in mechanical systems
- describe resonance in a musical instrument
- describe the natural frequency of an object
- identify the efficient transfer of energy in a resonating system.

You may have heard about singers who can break glass by singing particularly high notes. Figure 10.4.1 shows a glass being broken in this way. All objects that can vibrate tend to do so at a specific frequency known as their natural or **resonant frequency**. **Resonance** occurs when an object is exposed to vibrations at a frequency equal to its resonant frequency. This causes the amplitude of the resulting vibrations to increase significantly and transfers energy very efficiently. If the amplitude of the vibrations becomes too large, then the object can be destroyed. Resonance can happen for any kind of wave, not just sound waves.

FIGURE 10.4.1 A glass can be destroyed by the vibrations caused by a singer emitting a sound of the same frequency as the resonant frequency of the glass.

A swing pushed once and left to swing or oscillate freely is an example of an object vibrating at its natural frequency. The **natural frequency** of an object is the frequency at which an object will tend to vibrate when disturbed. In this case, the swing is disturbed by being pushed. The frequency at which it moves backwards and forwards depends entirely on the design of the swing, especially on the length of its supporting ropes. In time, the oscillations will fade away as the energy is transferred to the supporting frame and the air. Modifying these design properties, particularly length, allows many instruments to produce different notes, as explained in Modules 10.2 and 10.3.

If you watch a swing in motion, it is possible to determine its natural oscillating frequency. It is then possible to push the swing at exactly the right time so that you match its natural oscillation. The energy you add by pushing will increase the amplitude of the swing efficiently rather than work inefficiently against it. Over time, the amplitude will increase and the swing will go higher and higher, and resonate (Figure 10.4.2). The swing can only be pushed at one particular rate to generate this increase in amplitude (to get the swing to resonate). If the rate is faster or slower, the forcing frequency that you are providing will not match the natural frequency of the swing and you will not achieve an efficient transfer of energy.

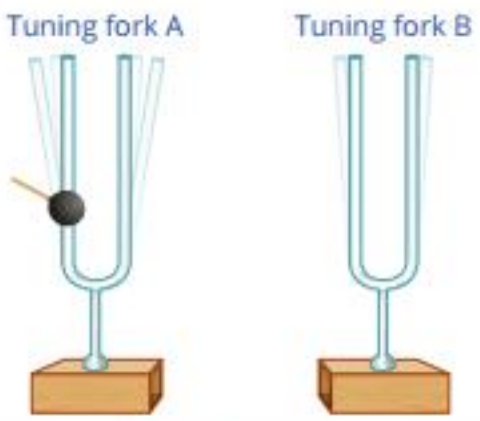
Other examples of resonant frequency that you may have encountered are blowing air across the mouthpiece of a flute or drawing a bow across a string of a violin in just the right place (Figure 10.4.3). In each case, a clearly amplified sound is heard when the frequency of the forcing vibration matches a natural resonant frequency of the instrument.

FIGURE 10.4.2 If you push a swing at its natural frequency, the amplitude of the swing increases, allowing it to swing higher.

Worked example 10.4.1

RESONANCE

Tuning fork A is struck with a mallet and begins to vibrate. Tuning fork B is identical to A and starts to vibrate without being struck. Explain why this happens.



Thinking	Working
Identify the frequency at which tuning fork A is vibrating.	When tuning fork A is struck, it vibrates at its natural frequency.
Identify how energy could be transferred from tuning fork A to tuning fork B.	The vibrations of tuning fork A make a sound. This sound wave travels through the air to tuning fork B, transferring energy.
Identify the frequency at which tuning fork B will vibrate.	The tuning forks are identical, so tuning fork B will have the same natural frequency as tuning fork A.
Explain how tuning fork B vibrates.	The forcing frequency (the sound wave from tuning fork A) is the same as the natural frequency of tuning fork B. This means that resonance occurs and so B vibrates, making a sound. Energy is transferred most efficiently when objects vibrate at their natural frequency.

FIGURE 10.4.3 The sound box of a stringed instrument is tuned to resonate for the range of frequencies of the vibrations being produced by the strings. When a string is plucked or bowed, the airspace inside the box vibrates in resonance with the natural frequency and the sound is amplified.

➤ Try yourself 10.4.1

RESONANCE

The sustain pedal on a piano allows the strings in the piano to vibrate freely. A pianist notices that when they have the sustain pedal pressed down a singer can make a string in the piano vibrate using only their voice. Explain why this happens.

Two very significant effects occur when the natural resonant frequency of an object is matched by the forcing frequency.

- The amplitude of the oscillations within the resonating object will increase dramatically.
- The maximum possible energy from the source creating the forced vibration is transferred to the resonating object.

Resonance can be quite destructive in a mechanical system. Like the wine glass in Figure 10.4.1, the increased amplitude in a vibration caused by resonance can cause violent vibrations beyond the device's capacity, leading to catastrophic failure. Resonance disaster can occur if the mechanical resonance of different components matches the natural frequencies of other components, thereby increasing their amplitudes until the components fail. In the design process, these natural frequencies need to be considered to avoid resonance disaster.

Acoustic engineers consider resonance in the design process. For example, useful forms of resonance are maximised in the design of a concert hall, but resonance is minimised in systems where the vibrations produced can cause destruction. In musical instruments and loudspeakers, resonance is a desired effect. The sounding boards of pianos and the enclosures of loudspeakers are designed to enhance and amplify particular frequencies. In other systems, such as car exhaust systems and suspension bridges, resonance is not desirable, and care is taken to design a system that prevents vibrations.

Worked example 10.4.2

MECHANICAL RESONANCE

The Millenium Bridge in London was closed shortly after its construction was completed. It was found to have a design flaw that caused it to oscillate as large numbers of people walked across it. Describe the physics behind this phenomenon.

Thinking	Working
Identify the forcing frequency in this situation.	The repeated movement of numerous people walking across the bridge had a specific frequency. This is the forcing frequency.
Identify the frequency at which the bridge would have vibrated.	The design of the Millenium Bridge gave it a specific natural frequency.
Identify how energy was transferred from the people to the bridge.	People transferred a small amount of energy to the bridge by exerting a force on it every time they took a step.
State the conditions for resonance to occur.	Resonance occurs if the forcing frequency matches the natural frequency of an object. In this case, the frequency of people walking matched the natural frequency of the bridge, which caused it to resonate.
Explain how the small movements of people walking caused the bridge to vibrate dangerously.	Resonance caused the small vibrations of people walking to transfer energy efficiently to the bridge, making it vibrate with increasing amplitude. This could have resulted in damage to the bridge.

➤ Try yourself 10.4.2

MECHANICAL RESONANCE

The Sydney Tower in Sydney has been fitted with a wave dampening device known as a mass damper. This device reduces vibrations caused by wind. Explain why this type of device is necessary.

10.4 Review

SUMMARY

- All objects that can vibrate tend to do so at a specific frequency known as their natural or resonant frequency.
- Resonance occurs when the frequency of a forcing vibration equals the natural frequency of an object.
- Two special effects occur with resonance:
  - The amplitude of vibration increases.
  - Energy is transferred efficiently from the source to the resonating object.
- Musical instruments are designed to use resonance to produce a clear, loud sound.

KEY QUESTIONS

Describe

1 Describe resonance.

Apply

2 Explain why resonance can result in damage to built structures.

3 A drinking glass vibrates when a finger is rubbed around the rim. Describe the energy transfers taking place.

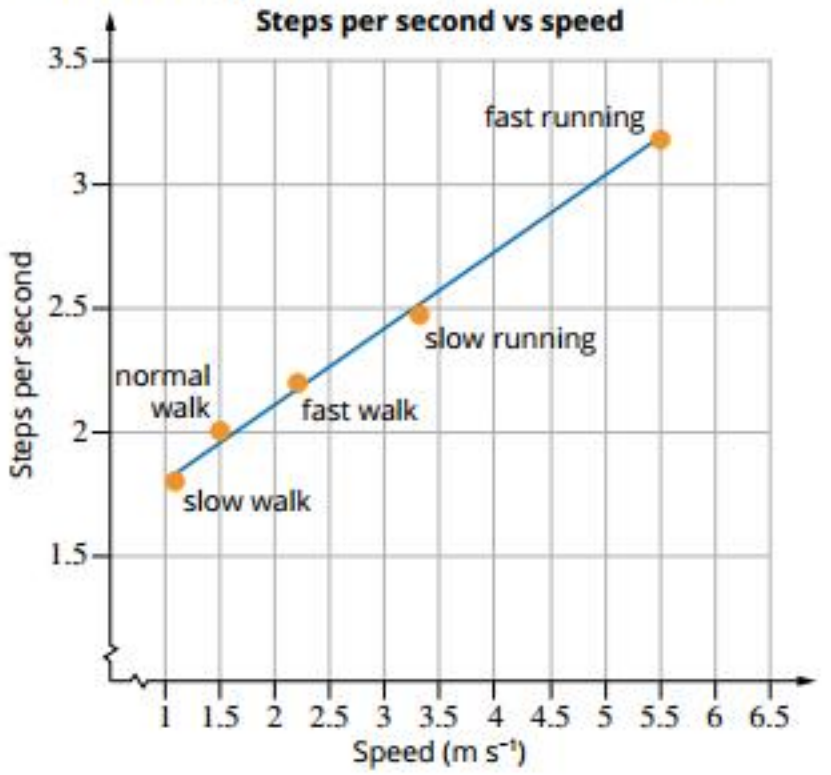
Analyse

4 On a swing, if you don't have someone to push you, you can also swing higher by swinging your legs and body with the natural frequency of the swing. Consider how this works.

5 The third harmonic of an open pipe is in resonance with the first harmonic of a pipe that is closed at one end. Calculate the length of the open pipe if the closed pipe is 12 cm long.

6 A footbridge over a river has a natural frequency of oscillation from side to side of approximately 1 Hz. When pedestrians walk at a pace that produces an oscillation in the bridge close to the natural frequency of the footbridge, resonance will occur.

The graph displays relevant data about pedestrians walking or running. A pedestrian completes 1 cycle of their motion every 2 steps. Determine which activity of the pedestrians is most likely to cause damage to the footbridge over time. Explain your answer.



Chapter review

10

KEY TERMS

elastic modulus
first harmonic
fundamental
harmonic
mechanical wave
medium
natural frequency
resonance
resonant frequency
standing wave

KEY QUESTIONS

Describe

1 Identify which of the following best describes sound.
- **A** transverse wave
- **B** electromagnetic wave
- **C** longitudinal wave
- **D** Mexican wave

2 True or False: Most sounds you hear are a combination of different frequencies.

3 A stretched string with two fixed ends has a fundamental frequency of 150 Hz. Determine the frequency of the third harmonic.
- **A** 600 Hz
- **B** 300 Hz
- **C** 50 Hz
- **D** 450 Hz

4 Recall which harmonics are possible for a string with a free end.
- **A** all harmonics
- **B** even harmonics ($n = 2, 4, 6, ...$)
- **C** odd harmonics ($n = 1, 3, 5, ...$)
- **D** no harmonics, just the fundamental frequency

5 A tuning fork starts to vibrate when a person sings a certain note. This vibration is an example of
- **A** resonance
- **B** dispersion
- **C** reflection
- **D** propagation

6 Resonance will only occur between two instruments if
- **A** the length of the two instruments is the same
- **B** the amplitude of the wave from each instrument is the same
- **C** the harmonic number of the wave produced by each instrument is the same
- **D** the frequency produced by one instrument matches the natural frequency of the other

Apply

7 Describe what happens to the amplitude and frequency of a wave during resonance.

8 Describe what happens to the speed of sound as the temperature of the medium increases.

9 Describe what a harmonic is.

10 Draw (to scale) the standing wave patterns for the first, second and third harmonics on a string (fixed at both ends) 10 cm long.

11 A standing wave pattern is shown below:

Which instrument produced this pattern?
- **A** A string fixed at both ends
- **B** A string with one end free
- **C** A pipe open at both ends
- **D** A pipe with one closed end

12 Many instruments come in different sizes such as soprano, alto, tenor and bass. Explain why all these sizes are made.

13 Describe the concept of resonance and why it would need to be considered when designing structures such as buildings or bridges.

14 Contrast the pattern created by the $L = n\frac{\lambda}{2}$ and $L = (2n - 1)\frac{\lambda}{4}$ equations for open pipes and pipes with a closed end as n increases.

15 Explain why the speed of sound in water is greater than the speed of sound in air.

Analyse

16 Assuming the speed of sound in water is 1500 $m s^{-1}$, calculate the wavelength of a sound at a frequency of 300.0 Hz.

17 The sound wave from Question **16** is now produced in air, where the speed of sound is 340 $m s^{-1}$. Calculate the new wavelength.

18 A string with two fixed ends has a length of 7.2 cm. Determine the longest wavelength that can be produced on this string.

A 1.4×10^{2} m

B 3.6×10^{1} m

C 1.4×10^{-1} m

D 3.6×10^{-2} m

19 A string with two fixed ends has a wavelength of 0.28 m when vibrating in the fourth harmonic. Calculate the length of the string.

20 A piccolo (a small flute) is a pipe with two open ends. Its length is 32 cm. Calculate:

a the fundamental wavelength

b the wavelength of the second harmonic.

21 A soprano saxophone is a pipe with one closed end and has a length of 40.0 cm. Calculate the wavelength of the third harmonic.

*Hint for questions **22** and **23**: The speeds of sound for different temperatures are in Table 10.1.2.*

22 Echolocation uses the speed of sound to determine how far away an object is. Echo sounders are used on boats to find out how deep the water is, or to locate fish. The echo sounder sends out a sound wave and detects the echo or reflection. The time between the sound and its echo is how long the wave takes to go from the boat to the bottom of the ocean and back. Determine how long it takes to receive a signal, if the water is 800.0 m deep at a temperature of 20°C.

23 A flute (a pipe with two open ends) has a length of 66 cm.

a Determine the frequency of the third harmonic if the air in the flute is at 20°C.

b Determine the frequency of the third harmonic if the air in the flute is now at 0°C.

c Using your answers to parts **a** and **b**, discuss why it is important to 'warm up' a musical instrument before adjusting the instrument to match frequencies with other instruments.

24 A pipe with one closed end is filled with air that resonates with a 400.0 Hz tuning fork. The length that corresponds to the fundamental frequency is 21.0 cm. Calculate the speed of sound in the pipe.

25 On a string with only one fixed end the wavelength of the fundamental frequency is 30.0 cm.

a Determine the relationship between the fundamental frequency on a string with only one fixed end and that on a string with both fixed ends.

b For the same length string, calculate the wavelength of the fundamental frequency if the string has two fixed ends.

c Determine whether this relationship holds for all harmonics.

26 A flute (a pipe with two open ends) produces a fundamental frequency of 440 Hz with a speed of sound of 350 m s^{-1}.

a Calculate the length of the flute.

b Calculate the length of a clarinet (a pipe with one closed end) that would produce the same fundamental frequency (same speed of sound).

27 An earthquake causes a footbridge to oscillate up and down with a fundamental frequency once every 4.0 s. The motion of the footbridge is like that of a string fixed at both ends. Determine the frequency of the second harmonic for this footbridge.

28 The speed of waves in a particular string at constant tension is 78 m s^{-1}. The string is fixed at both ends. If a particular frequency of a standing wave formed in the string is 428 Hz, calculate how far apart two adjacent antinodes would be.

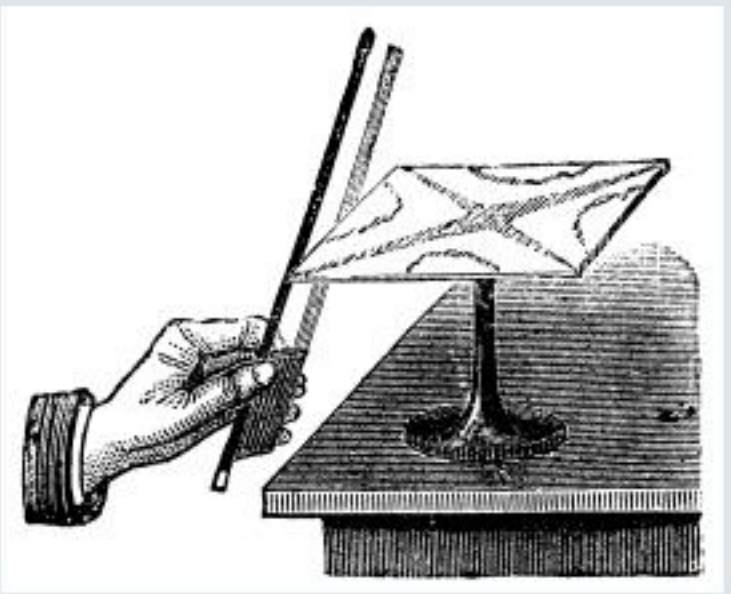
29 On Earth, a pipe instrument open at both ends has a natural frequency of 256 Hz at an air temperature of 25°C (v = 346 m s^{-1}). On Venus, the speed of sound is 410 m s^{-1}. Calculate the natural frequency the pipe instrument would have on Venus.

30 Use the internet to explore how resonance is used to help protect large buildings in earthquake-prone areas.

Interpret

31 The speed of sound can be measured by taking advantage of echoes. Design an experiment to use echoes to measure the speed of sound.

32 An interesting way to visualise sound, and as an engaging science demonstration, is the use of Chladni plates, shown below. Research how these work and design a demonstration to use these.



33 A common investigation of resonance involves holding a vibrating tuning fork over a measuring cylinder. The measuring cylinder is then filled with water until resonance is discovered. The distance from the top of the cylinder to the water level can be recorded and used in the closed pipe formula and compared for different frequencies of tuning fork. Modify (redirect) this experiment to investigate the relationship between speed of sound and frequency instead of length.

Data analysis

DATA SET 1

The information below applies to Questions 1–3.

A student conducted an experiment to answer the following research question:

What is the relationship between the natural frequency and the length of an open-ended pipe?

The student has conducted the experiment, collected the data, and presented it in Figure 1 below.

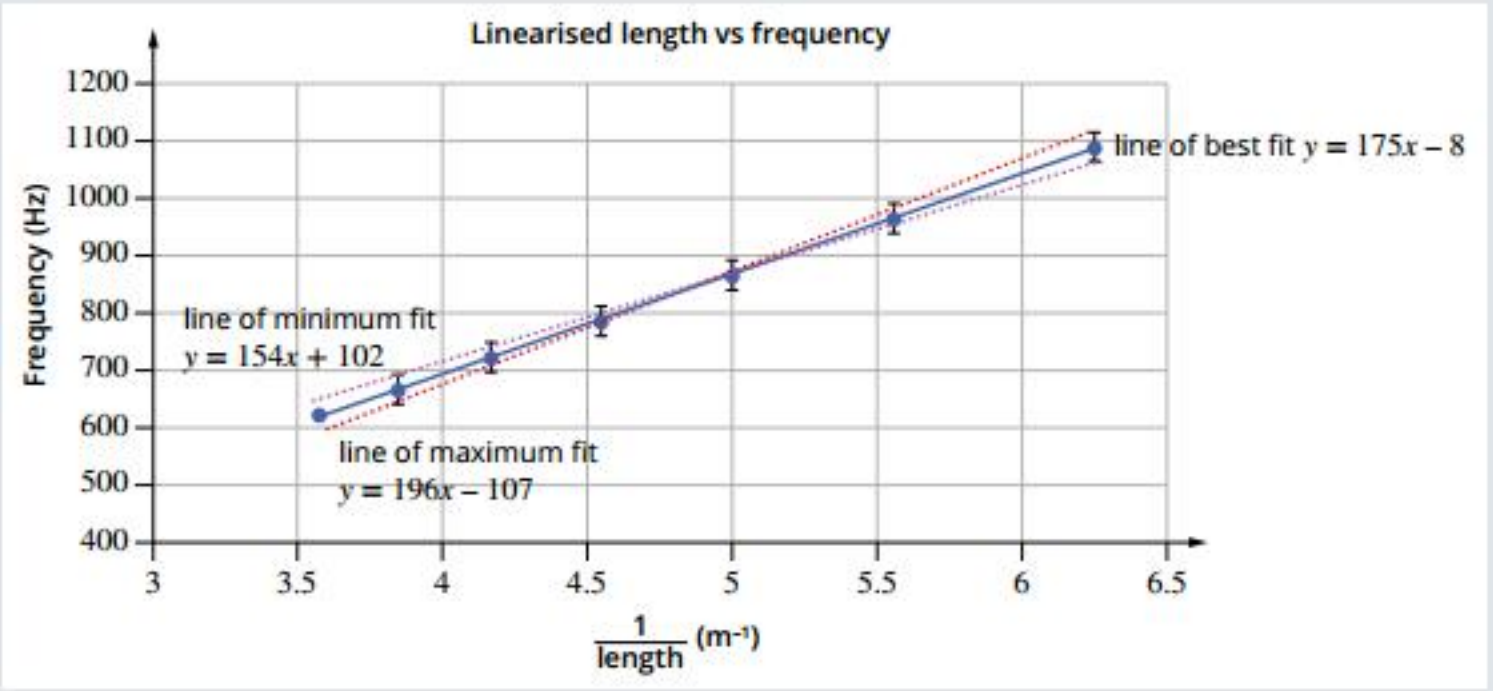


FIGURE 1 Linearised length vs frequency in an open-ended pipe

Question 1 (3 marks)

Identify the mathematical relationship between frequency and the length of the pipe, including the uncertainty of the gradient and *y*-intercept.

Question 2 (4 marks)

Draw a conclusion that quantifies the speed of sound, including the absolute uncertainty in the value. Show your reasoning.

Question 3 (3 marks)

Evaluate the accuracy and precision of the experiment given it was conducted at a temperature of 25°C in air.

CHAPTER

11 Light

A model is a system used to build a picture or an analogy for an observed phenomenon. In this chapter you will explore models for the behaviour of light. A good model will fit and explain all known observations and will, ideally, be able to predict new behaviours. This chapter looks at the development of a wave model to understand the nature of light and its application to key observations. The behaviour of light will be compared to that of a mechanical wave. This will lead to explanations of various light wave phenomena including reflection, refraction, dispersion, interference, diffraction and polarisation.

Syllabus subject matter

LIGHT

- Compare light to a mechanical wave. **11.1, 11.2**
- Explain the concepts of reflection, refraction, total internal reflection, dispersion, diffraction and interference in relation to the wave model of light. **11.1, 11.3, 11.4, 11.5**
- Describe polarisation using a transverse wave model. **11.7**
- Construct ray diagrams to demonstrate the reflection and refraction of light. **11.3, 11.4**
- Solve problems involving the reflection of light on single plane mirrors and refraction of light through a single convex or concave lens using ray diagrams to identify the location, orientation and size of an image. **11.3, 11.4**
- Describe the concept of Snell's Law. **11.4**
- Solve problems involving the refraction of light at the boundary between two mediums using $\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$ **11.4**
- Contrast the speed of light and the speed of mechanical waves. **11.1**
- Describe the concept of intensity and its proportionality to the square of amplitude. **11.6**
- Solve problems involving the proportional relationship between intensity of light and the inverse-square of the distance from the source using $I \propto \frac{1}{r^2}$. **11.6**
- Determine the refractive index of a transparent substance from experimental data. **Data analysis 11**

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11.1 Light as a wave

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- compare light to a mechanical wave
- describe two models for the nature of light
- explain the propagation of light by particles and waves
- describe reflection and refraction as evidence for both the particle and wave models of light
- state that whether light can be modelled as a particle or wave depends upon the speed of light
- state that a transverse wave model of light can be used to explain other wave behaviours of light.

Human interest in the nature of light dates back to the ancient Greek, Arabian and Chinese philosophers – and scientists have been curious about it for centuries. In the early 19th century, evidence suggested that light could be modelled as a wave because it exhibited the same set of properties as other phenomena that had already been defined as waves: water waves, sound waves, vibrations in springs and strings. If light exhibits sufficient properties in common with these known waves, then surely it too could be assumed to 'be' a wave?

Recall from Chapter 9 that light cannot be a mechanical wave because a mechanical wave needs a medium in which to travel. Light can travel through a vacuum and does not need a medium. This observation resulted in two conflicting theories, both from the later 1600s.

- English scientist Sir Isaac Newton explained light in terms of particles or 'corpuscles', with each different colour of the **spectrum** representing a different type of particle.
- Robert Hooke (from England) and Christiaan Huygens (from Holland) proposed an alternative model that described light as a type of wave, similar to the water waves observed in the ocean.

A key point of difference between the two theories was that Newton's **corpuscular** theory suggested that light would speed up as it travelled through a solid material such as glass. In comparison, the wave theory predicted that light would travel more slowly through glass than through air.

At the time it was impossible to measure the speed of light accurately, so the question was not resolved scientifically. Newton's more eminent reputation meant that, for many years, his corpuscular theory was considered correct and it was not until the early 19th century that experiments convincingly demonstrated the wave properties of light.

MODELLING WITH PARTICLES

Light streaming through trees on a misty morning, the projector's beam in a dusty cinema, the limited view when peeping through a keyhole and the distinct shape of shadows are all evidence for the straight-line (rectilinear) path of light. These examples show that, when transmitted in a uniform medium, light travels in straight lines. A uniform medium is a substance that is unchanging in its constitution. Awareness of the **rectilinear propagation** of light enables people to judge the distance to objects. The mechanism by which the eyes and brain interpret a three-dimensional world is complex, but it relies on the assumption that light in a uniform medium travels in straight lines.

The following simple experiment can be performed to demonstrate that light travels along a straight path in a uniform medium. Make a pinhole in each of three identical pieces of card. Place card A close to a light source, and position card B a little further away, as shown in Figure 11.1.1. Then, holding card C in front of your eye so that you can always see through the hole, adjust its position so that you can see the light from the lamp. This will only be possible when all three pinholes lie in the same line and are **collinear**. The conclusion that can be drawn is that light must travel in straight lines.

The above property of light was first modelled by considering that light was particle-like in nature. Consider a beam of light shining from a powerful torch. Rays can represent the direction of travel of the light 'particles'. The idea of a light ray is a useful concept, as it can successfully model the behaviour of light. A beam of light can be thought of as a bundle of rays. A strong light source, such as the Sun, could therefore be thought of as producing a very large number of light rays.

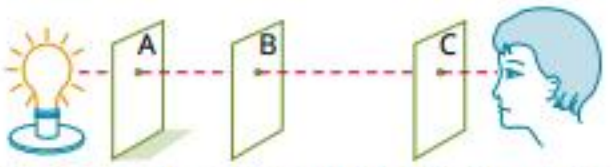


FIGURE 11.1.1 Light from the lamp can only be seen if the pinholes A, B and C lie in a straight line. This means that light must travel from the lamp to the eye along a straight line.

MODELLING LIGHT AS A TRANSVERSE WAVE

During the 17th century, when Newton was studying the nature of light, it was known that light had the following properties:

- Light travels in straight lines in a uniform medium (referred to as linear propagation).
- Light obeys the law of reflection.
- Light obeys Snell's law of refraction.

Reflection and refraction, along with other wave behaviours of light, will be investigated in more depth in later modules of this chapter.

Huygens' principle

Recall from Module 9.4 that Huygens' principle states that each point on a plane or circular wavefront can be considered as a source of secondary wavelets (small waves). These wavelets spread out in the forward direction at the same speed as the source wave.

Huygens noted that the envelope or common tangent of the wavelets becomes the new wavefront. The path of a point on any one wavelet will be in a straight line and accounts for the straight-line rays observed as light travels from a source. Light could be modelled as a transverse wave.

Modelling reflection

Reflection can be modelled either as particles or as a wave. If light is a wave, reflecting light behaves just as water waves do when striking a barrier. The laws of reflection are obeyed, and the reflection of light is modelled just as effectively as with a particle approach, as shown in Figure 11.1.2.

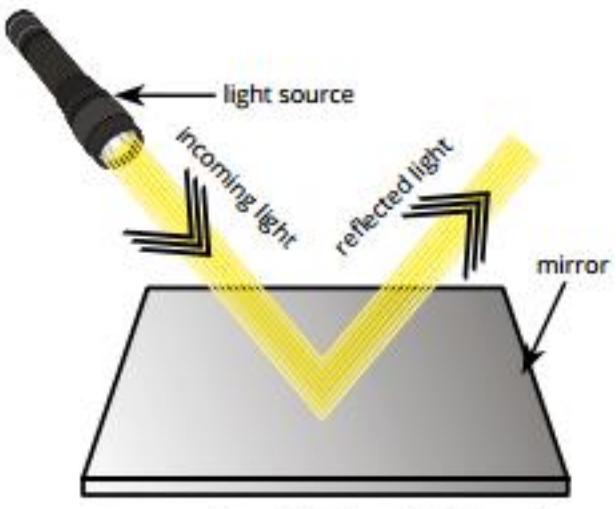


FIGURE 11.1.2 The reflection of light can be modelled by considering light as a wave, as Huygens predicted.

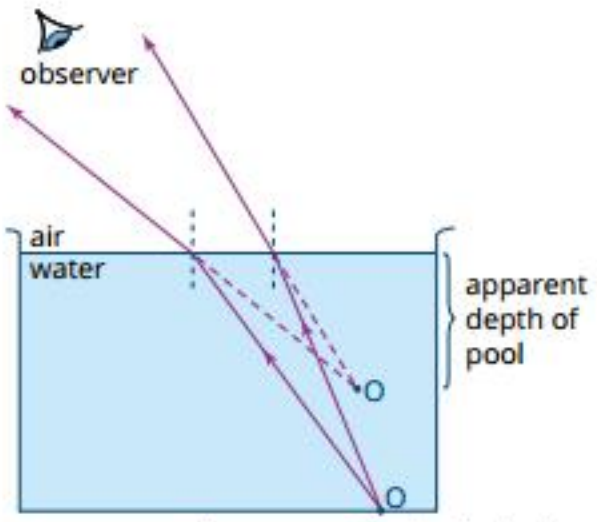


FIGURE 11.1.3 The apparent depth of a body of water appears less than its actual depth because of refraction. Light rays from a point at the bottom of the pool are refracted at the water's surface. The observer perceives these rays to have come from an elevated location and interprets this to mean that the water is shallower than it really is.

Modelling refraction

Modelling refraction of light as a wave was not as simple. The bending or change of direction of light as it passes from one medium to another is called refraction (Figure 11.1.3). **Refraction** occurs because light changes speed as it enters a medium with a different **optical density**. Various common phenomena are caused by refraction. Examples include the bend that appears in a straw when it is standing in a glass of water, the strangely shortened appearance of your legs as you stand in a waist-deep swimming pool, and the 'puddles of water' that you see on the road ahead on a warm day.

In Module 9.4 you studied the refraction of waves, including light waves. Refraction can be modelled by the movement of particles or by the movement of waves. In the 18th century—more than a century after it was developed—Newton's particle (or 'corpuscular') model was more popular than the wave theory, and most of the progress in understanding the nature of light at that time was made based on his theories. Newton's prestige also added weight to his arguments. After all, he had been shown to be right so many times before, so why would he be wrong now?

The behaviour of light as it moved from air into another transparent medium, such as glass, could provide evidence for either model. If light was made of particles then, for refraction to occur with the light bending towards the normal—as was observed—it would have to move faster in the optically denser medium than in air. However, if light were waves, it would move more slowly in the denser medium.

It seemed that the only way to separate the two theories was to measure the speed of light in both air and the other medium. If light was slower in air, then the particle theory would be validated. However, Newton was unable to measure the speed of light to prove this. It was not until 1850 that measurements could confirm the speed of light (approximately $3 \times 10^8 \text{m s}^{-1)}$ and that light slowed down when travelling through an optically denser medium. Huygens' wave model, therefore, appeared to be supported; light could be modelled as a transverse wave. But, by then, the wave nature of light was well established by the work of other scientists observing and measuring its wave-based behaviours—such as dispersion, diffraction, interference and polarisation—and Newton's particle model was all but forgotten.

It is useful to use a wave model for light; however, it is important to understand that light is *not* a mechanical wave. A light wave shares many characteristics with mechanical waves—such as having a frequency, wavelength, amplitude and speed—but an experiment at the end of the nineteenth century by physicists Albert Michelson and Edward Morley proved that light does not need a medium to travel through. Travelling through a medium is, on the other hand, a crucial characteristic of mechanical waves. Later studies in Unit 4 Physics will examine the exact nature of light waves.

11.1 Review

SUMMARY

- In the 1600s, two models for the nature of light were proposed: particles (developed by Newton) and waves (developed by Huygens).
- Rays can be used to represent the direction in which light travels.
- Reflection and refraction provide evidence for a model of light as either particles or waves.
- Measurements of the speed of light confirmed its speed as approximately $3 \times 10^8 \, m s^{-1}$, many magnitudes faster than mechanical waves.
- Measurement of the reduction in the speed of light when refracting in a more optically dense medium confirmed a wave model for light.
- Further investigations confirmed that a transverse wave model for light could explain other wave properties including dispersion, diffraction, interference and polarisation.
- Light has many wave characteristics, such as frequency, wavelength and speed, but is not a mechanical wave as it does not require a medium in which to travel.

KEY QUESTIONS

Describe

1 State the graphical method by which the straight-line propagation of light can be represented.

2 The apparent depth of a body of water appears less than its actual depth when viewed from above. Identify the behaviour of light that contributes to this observation.

Apply

3 Refraction can be explained in part by either a wave model or a particle model of light. Describe what the key difference was that established that the refraction of light could be explained by a wave model rather than by the particle model.

4 Describe what Huygens considered to have happened at each point on a plane or circular light wavefront.

5 Explain why light cannot be described as a mechanical wave.

Analyse

6 Consider the different observed behaviours of light noted in this module. Sort each behaviour as supporting either a particle or a wave model. Include any specific constraints that apply for the behaviour to apply to the particular model.

Supports particle model	Supports wave model

7 Using a mirror makes it possible to see around a corner. Does this contradict the rectilinear (straight-line) propagation of light? Explain your answer.

11.2 The electromagnetic spectrum

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- Understand the properties and behaviour of light as an electromagnetic wave rather than a mechanical wave
- Compare light to a mechanical wave.

By the late 1600s, light was known to involve the transfer of energy from one place to another. In Isaac Newton's time, a corpuscular (particle) model and a wave model for light seemed equally valid. In spite of considerable experimentation by scientists it was not until the early 1800s that one model prevailed.

Thomas Young discovered that sources of light were able to interfere with each other, just like sound waves and water waves, which are both mechanical waves. It was this finding that led to a universally accepted wave theory for light. Furthermore, with the work of Michelson and Morley and others, the speed of light had been measured for the first time, and the wave model of refraction could be validated. Meanwhile, another area of physics had been developing. By the 1860s, investigations led to the finding that **visible light** was just one of the many forms of **electromagnetic radiation** (EMR).

ELECTROMAGNETIC RADIATION

Electricity and magnetism were once considered to be completely separate phenomena. It was then discovered that:

- a moving charge will create a magnetic field
- a changing magnetic field can be used to create electricity.

In 1864 James Clerk Maxwell used mathematical equations to describe how charges moving periodically in a conductor would set up alternating electric fields and magnetic fields in the nearby region. Maxwell knew that the magnetic and electric fields travelled through space. He calculated their speed as $3.0 \times 10^8\,\text{m s}^{-1}$, the same as the speed of light. He went further to devise mathematical expressions to describe the magnetic and electric fields. The solution to these expressions was found to be the same as the equation of a wave. Maxwell had demonstrated that light is an electromagnetic wave.

It is now known that light exists at a wide range of frequencies (or wavelengths) called the **electromagnetic spectrum**. These all travel at the same speed, $3.0 \times 10^8\,\text{m s}^{-1}$. Recall from Chapter 9 that for any wave the relationship between its frequency, f, and its wavelength, λ, is given by $v = f\lambda$, where v is the speed of the wave in a given medium. This is called the wave equation. All EMR travels at a speed of $3 \times 10^8\,\text{m s}^{-1}$ in a vacuum, and so this significant speed has been allocated the special symbol c. This can be used in a special form of the wave equation, $c = f\lambda$, which can be rearranged to $f = \frac{c}{\lambda}$. This can be used to calculate the frequency or wavelength for EMR.

For all electromagnetic radiation:

$$f = \frac{c}{\lambda}$$

where

f is the frequency (Hz)
c is the speed (approximately $3 \times 10^8\,\text{m s}^{-1}$)
λ is the wavelength (m).

Worked example 11.2.1

APPLYING THE WAVE EQUATION TO EMR

A sample of sodium burned in a flame produces light with a wavelength of 589 nm. Determine whether the frequency of this light is within the visible range.	
Thinking	**Working**
Recall the special case of the wave equation for EMR.	$f = \frac{c}{\lambda}$
Substitute the appropriate known values into the formula and solve.	$c = 3 \times 10^8\,\text{m s}^{-1}$ $\lambda = 589\,\text{nm} = 589 \times 10^{-9}\,\text{m}$ $f = \frac{3 \times 10^8}{589 \times 10^{-9}}$ $= 5.09 \times 10^{14}$ $= 509 \times 10^{12}\,\text{Hz}$
Refer to Figure 11.2.1 on page 422 to determine if the frequency is within the visible range.	This frequency is in the visible range of the EMR spectrum, around 10^{12} Hz.

➤ Try yourself 11.2.1

APPLYING THE WAVE EQUATION TO EMR

A sample of copper burned in a flame produces light with a wavelength of 492 nm. Determine whether the frequency of this light is within the visible range.

TYPES OF ELECTROMAGNETIC RADIATION

This spectrum is roughly divided into seven categories, depending on how the radiation is produced and the frequency of the waves. These boundaries shouldn't be thought of as exact, but they do provide a convenient means of identifying the properties of the EMR in each section. For example, human eyes can respond to EMR of frequencies between approximately 400×10^{12} Hz and 800×10^{12} Hz. These frequencies are referred to as the visible light section of the electromagnetic spectrum.

The energy carried by the EMR is proportional to its frequency.

- High-frequency, short-wavelength gamma rays are at the high-energy end of the spectrum.
- Low-frequency, long-wavelength radio waves carry the least energy.

Figure 11.2.1 on page 422 shows the different categories of EMR. Note the vast range of frequencies and wavelengths. The range of frequencies (or wavelengths) constituting visible light occurs near the middle of the spectrum. Human eyes cannot perceive any wavelengths of EMR outside of this range.

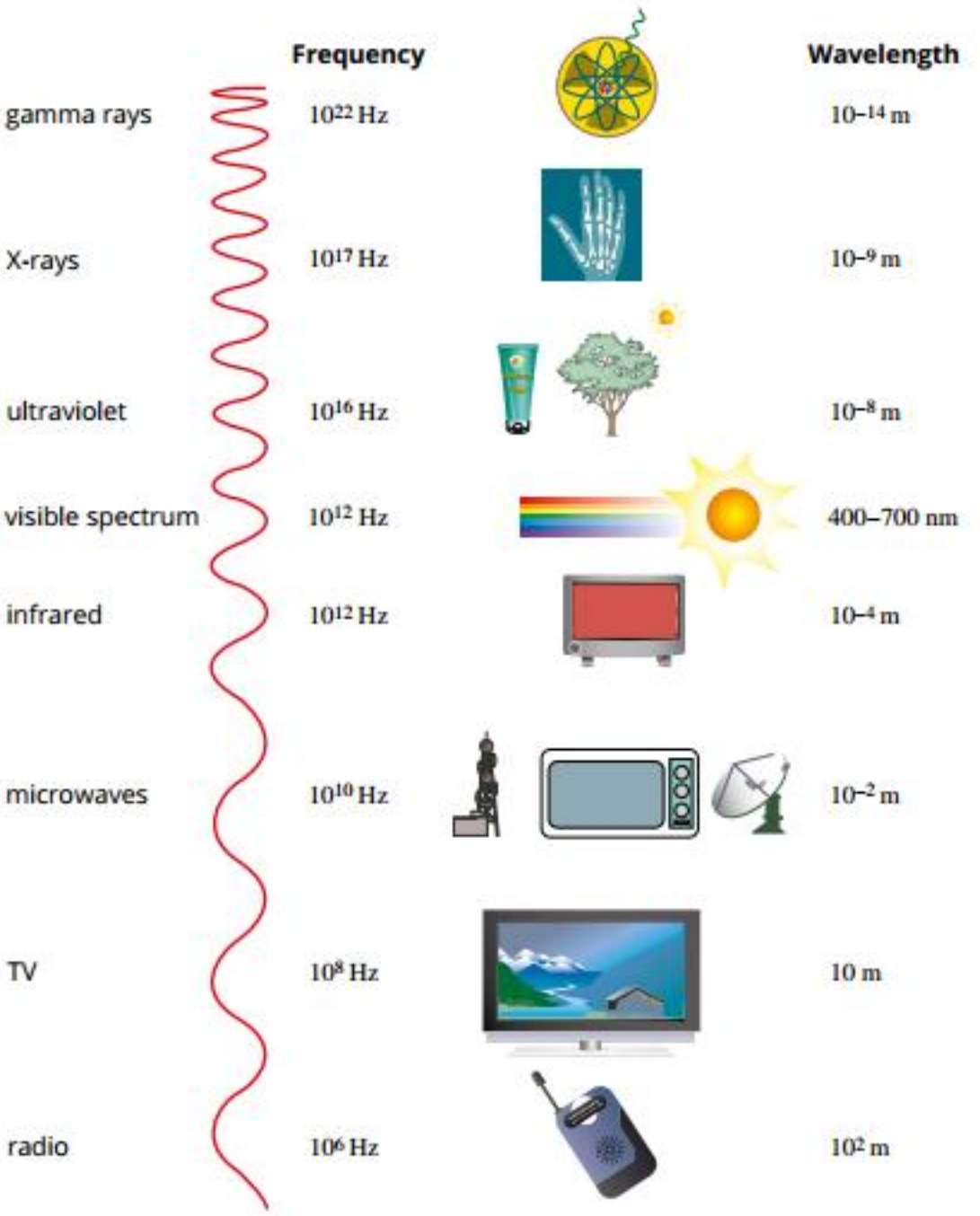


FIGURE 11.2.1 The electromagnetic spectrum. In this representation the radio wave section of the spectrum is broken down into two sections: TV and radio.

Visible light

Within the visible section of the spectrum, human eyes are responsive to many different colours of light from the deepest red through to the brightest violet. In fact, the human eye can distinguish about 10 million different colours.

Each variation in colour or shade is caused by light of a different wavelength. Traditionally the colours quoted as making up the visible spectrum are red, orange, yellow, green, blue and violet, present in approximately equal proportions. However, as shown in Figure 11.2.2, the actual allocation of separate names for the colours is not as clear-cut as many people think, because the colours merge into one another. The wavelengths associated with visible light are very small. They range from approximately 390 nanometres (or 390×10^{-9} m) for violet light to about 780 nanometres for red light.

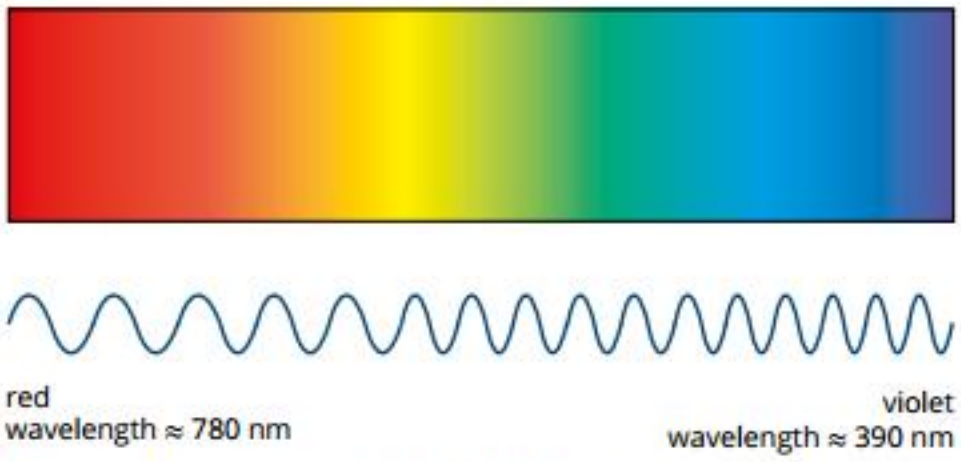


FIGURE 11.2.2 Visible light is one category of EMR. The spectrum of visible light contains a myriad of colours. Each different colour or hue is light of a different wavelength.

The colour of an object that people see is a physiological response to the particular wavelength(s) of light entering the eyes. A human being's colour-sensing system, consisting of the eye, nerve conductors and the brain, can discriminate between millions of different colours. However, different combinations of wavelengths of light can evoke the same response from the brain. In other words, there are several different ways in which to make an object appear a particular shade of colour.

The colour of an object is determined by the colours of light it reflects and absorbs when white light, evenly distributed across the visible spectrum, is shone upon it. When an incident ray of light strikes the surface of an object it may be absorbed, transmitted and/or reflected.

- If all the white light falling on a surface is reflected, then the object will appear white.
- If all the white light falling on a surface is absorbed, then the object will appear black because no light is reflected.
- If all the white light falling on a surface is absorbed except for blue, then the object will appear blue because this is the only light that is reflected.

You perceive light as white light if it contains roughly equal amounts of each of the colours of the visible spectrum. The page of this book appears white because it is reflecting all the colours (wavelengths) of visible light in roughly equal proportions.

Sunlight, incandescent light and fluorescent light all produce the same general sensation of white light. The light from incandescent and fluorescent globes does not appear to be as white as sunlight. This is because sunlight is very evenly distributed across the spectrum, but an incandescent source radiates considerably more red light than blue, and a fluorescent source radiates more blue light.

Radio waves

Accelerating a positive or negative charge can produce EMR. Electrons oscillating in a conducting wire, such as an antenna, produce the radio waves that bring, for example, sports broadcasts to your radio. These long-wavelength, low-energy electromagnetic waves blanket the surrounding region, and aerials can receive the signal many kilometres from the source. As a result of the radio waves, electrons in the receiving aerial will oscillate, producing a current that can be amplified. Radio waves can be transmitted over very long distances, including around the Earth, by reflection from layers of the atmosphere.

Radio waves are the lowest energy EMR, so they are also the most common form of energy emitted by interstellar objects. They are a major focus of studies seeking to determine the evolution, shape and size of the universe (Figure 11.2.3).

FIGURE 11.2.3 The Murchison Widefield Array (MWA) is a low-frequency radio telescope located in Western Australia, operating between 80 and 300 MHz and conducting large-scale surveys of the southern sky.

Microwaves

Microwaves are EMR with wavelengths ranging from about 1 mm to about 10 cm. The microwaves that cook your food are produced by the spin of an electron or nucleus. Microwave links are also used for communication between locations over long distances, and radar equipment uses microwaves of centimetre wavelengths to locate distant objects by measuring the strength and direction of reflected signals.

Infrared waves

Infrared or heat radiation includes the wavelengths that are emitted by every object at a temperature above absolute zero. When you feel the warmth of the Sun or a heater, your skin is detecting infrared radiation. The hotter the object, the more radiation that is emitted and the higher the frequency of the radiation.

Night scopes and infrared spy satellites create an image by sensing infrared radiation and converting it into a visible picture.

Ultraviolet waves

Ultraviolet waves have wavelengths shorter than the violet that eyes can see, but no greater than about 10 nm. Many insects and birds can detect ultraviolet light that is commonly reflected from flowers, allowing potential pollen sources to be located. Although ultraviolet light is less energetic than gamma rays and X-rays, it is known to cause skin cancer, particularly with increased time of exposure.

X-ray waves

X-rays initially got their name as a result of scientists not knowing what they were when they were first detected. They are produced when fast-moving electrons are fired into an atom. X-rays are high-energy radiation that can pass through body tissue and so are used in medical diagnosis. In industry, X-rays are used for safety testing, security, quality control and, increasingly, as a means of investigating structures at the subatomic level, including that of DNA.

Gamma-ray waves

The highest energy, shortest wavelength radiation is the gamma ray, produced within the nucleus of an atom. Gamma rays are one of three types of emissions that result from radioactive decay. Gamma rays can penetrate through a considerable depth of most materials and require dense materials, such as lead, to absorb them.

11.2 Review

SUMMARY

- Electromagnetic radiation (EMR) can be modelled as a transverse wave propagated by electrical and magnetic fields at right angles to each other. Unlike mechanical waves, it does not need a medium in which to travel.
- All EMR travels at a speed, c, of $3 \times 10^8 \text{ m s}^{-1}$ in a vacuum. A form of the wave equation, $f = \frac{c}{\lambda}$, gives the relationship between frequency and wavelength of EMR.
- Visible light is only a small part of the electromagnetic spectrum. The many forms of EMR are essentially the same, their properties differing as a result of their frequency and, hence, wavelength.
- From longest to shortest wavelength, the seven parts of the electromagnetic spectrum are radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.
- White light contains red, orange, yellow, green, blue and violet light in approximately equal proportions.

KEY QUESTIONS

Describe

1 State the approximate range of frequencies included in the EMR category of visible light.

2 List the seven categories of electromagnetic radiation in order from longest wavelength to shortest wavelength.

3 Recall the equation used to determine the wavelength of light of a given frequency.

4 All light shone onto an object is absorbed. What colour does the object appear to be?

Apply

5 Two sources of electromagnetic radiation have wavelengths of 450 nm and 780 nm respectively. Explain why the 780 nm radiation has the lower energy.

6 Explain why X-rays are used for medical imaging.

7 Explain why humans cannot see gamma rays.

Analyse

8 Calculate the wavelength of:

a microwaves of frequency 3×10^{10} Hz.

b ultraviolet radiation of frequency 1×10^{15} Hz.

9 Infrared radiation has wavelengths between 700.0 nm and 1.00 mm. Calculate the corresponding range of frequencies of infrared radiation, based on the limiting values of 700.0 nm and 1.00 mm.

10 The seven sections of the electromagnetic spectrum have differences and similarities. Give two differences and two similarities.

11.3 Reflection of light

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state that a wave model of light can explain reflection
- state the law of reflection
- apply the ray and wave models to the reflection of light
- construct ray diagrams to demonstrate the reflection of light
- construct ray diagrams to solve problems involving the reflection of light on plane and curved mirrors.

MODELLING REFLECTION

The reflection of waves was explained in Chapter 9. Light has been observed to obey the same laws of reflection that apply to waves and so evidence is provided for the argument that light is a wave.

Using a wave model, the reflection of light would be represented as a series of wavefronts striking a surface and then being reflected on the surface. However, it is far more common to model the reflection of light using ray diagrams and the conventions associated with them, as shown in Figure 11.3.1. Creating a model for the path of light and the formation of images in optical systems is far simpler using **geometrical optics** rather than a wave-optics approach.

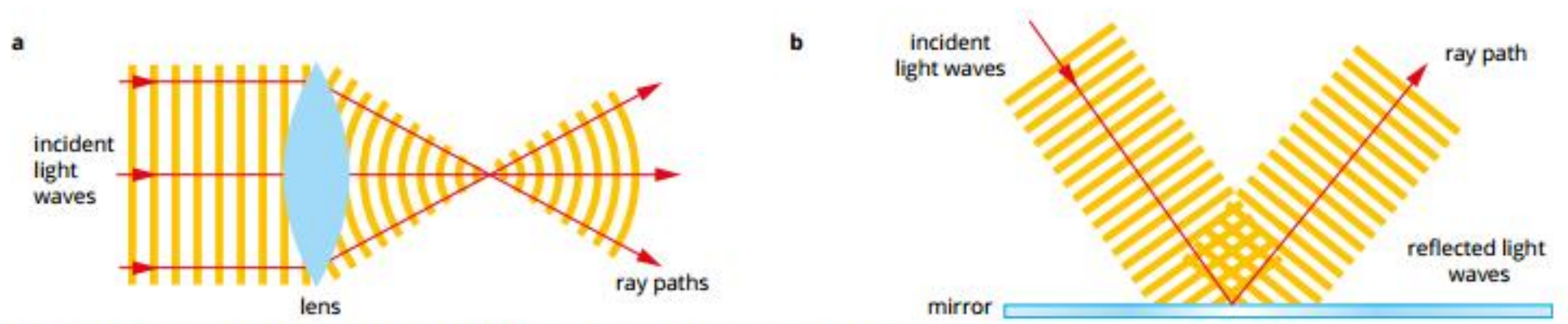


FIGURE 11.3.1 The path of light through many optical systems involving lenses and mirrors can be accurately represented using rays.

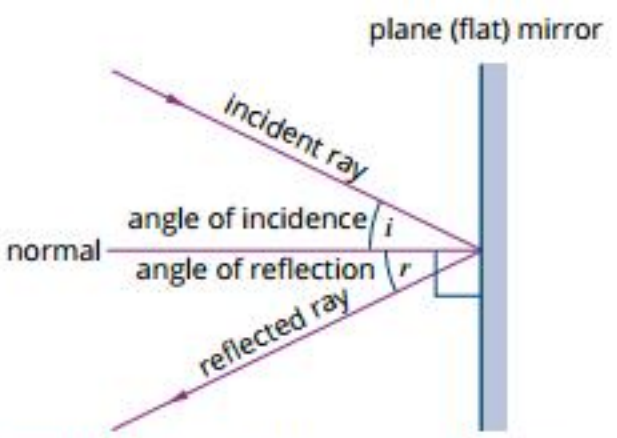


FIGURE 11.3.2 When light reflects from a plane mirror, the angle of incidence equals the angle of reflection: $i = r$.

Consider the plane mirror drawn in Figure 11.3.2.

- A normal to the surface of the mirror is defined as the line perpendicular (at 90°) to the mirror's surface at the point where an incoming or incident ray strikes the surface of the mirror.
- The angle between an incident ray and the normal is the angle of incidence, denoted i.
- The ray strikes the mirror and reflects with an angle of reflection, r, which is the angle between the reflected ray and the normal.

Experiments show that whenever reflection occurs, the angle of incidence always equals the angle of reflection. In addition, the light reflects in such a way that the incident ray, the normal and the reflected ray all lie in the same plane. The law of reflection can then be re-stated using a ray model for light.

The law of reflection states that the angle of incidence, i, is equal to the angle of reflection, r ($i = r$). The incident ray, the normal and the reflected ray will all lie in the same plane.

IMAGES IN PLANE MIRRORS

When considering the images formed in a mirror, it is helpful to distinguish between seeing an image directly and seeing an image of the object in the mirror.

When a person stands in front of a plane mirror, light from a point on their foot will travel to the mirror and be reflected. All rays obey the law of reflection, and a pair of slightly diverging rays can be traced as they leave the foot, reflect from the mirror and return to the observer's eyes. To form an image, the observer's eyes focus the diverging light rays and the brain interprets the rays as having come from a single point behind the mirror. This is where the image is seen in the mirror.

Figure 11.3.3 illustrates geometrically how the eye and brain subconsciously extrapolate diverging rays of light until they meet and are interpreted as an image.

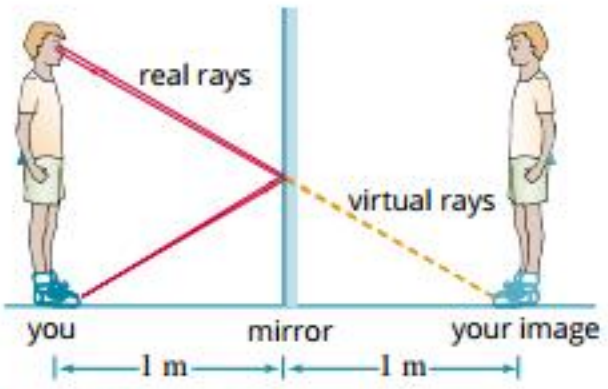


FIGURE 11.3.3 Diverging reflected rays are focused by the eye and the brain interprets the rays as having come from a single point behind a mirror.

It is important to note that the rays behind the mirror are not actually there. They are virtual rays, and by convention they are shown as dashed lines. When an image forms behind an optical element such as a mirror, it is classified as a **virtual image**. Other optical systems form a real image where the rays converge to meet. A **real image** can be shown on a screen, like an image from a movie projector. Virtual images cannot be projected onto a screen.

The **ray tracing** exercise shown in Figure 11.3.3 can be repeated for all parts of the body to locate the complete image of the whole person. A corresponding image point matches every point on the object. Each image point is the same distance behind the mirror surface as the object is in front. The object and the image are the same size. All images formed by plane mirrors have the following characteristics:

- The image is always upright.
- The image is the same distance behind the mirror as the object is in front.
- The image is the same size as the object.

Lateral inversion

The image that you see in a mirror is not exactly what you look like. The geometry of reflection means that images are reversed from left to right, in a process known as lateral inversion. If you stand in front of a mirror and hold up your right hand, it will appear as if your image is holding up its left hand, as shown in Figure 11.3.4.

Unlike a mirror image, a photo of your face is not laterally inverted, so it will look slightly different from the face that you are used to seeing in the mirror. However, the differences may not be so great that you consciously notice them. Instead, you might just feel like something is 'wrong' with the photo.

FIGURE 11.3.4 Although the woman is applying makeup with her right hand, in her image she appears to be applying it with her left hand.

CURVED MIRRORS

The applications of plane mirrors in everyday life are limited by the features of the image that can be produced. For example, the image in a plane mirror is always the same size as the reflected object, so a plane mirror will not produce a **magnification**. Curved mirrors provide a greater variety of options, depending on the extent and sense of the curvature of the mirror and the placement of the object, as shown in Figure 11.3.5. Shop-security mirrors, shaving and make-up mirrors and dentist's mirrors all use a curved mirror to produce an image that is appropriate for the situation in which it is used.

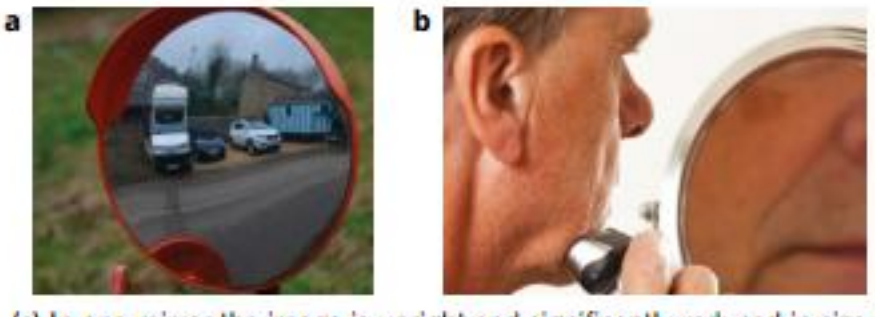


FIGURE 11.3.5 (a) In one mirror the image is upright and significantly reduced in size. (b) The image in the other mirror has been magnified. Both are examples of the application of curved mirrors.

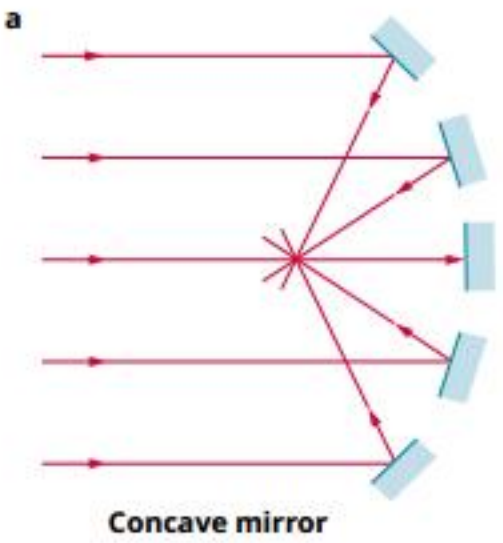


FIGURE 11.3.6 Each ray obeys the law of reflection, resulting in (a) converging reflected rays or (b) diverging reflected rays. In each case, a focal point can be defined. A concave mirror has a real focus, and the focal length is positive. The focus for the convex mirror is virtual because its position is determined by extrapolating the reflected rays behind the mirror.

All curved mirrors are either **concave** or **convex**. The **focal length** of a mirror is the distance from the mirror at which a parallel beam of light is brought to a focus.

- A concave mirror is curved like the inside of a spoon and is converging. When parallel rays of light are reflected at the surface of the mirror, the rays focus to a point in front of the mirror. Concave mirrors have a real focal point in front of the mirror, as shown in Figure 11.3.6a.
- A convex mirror is shaped like the back of a spoon and is diverging. When parallel rays of light are reflected at the surface of the mirror, the rays spread out in front of the mirror. Convex mirrors have a virtual or imaginary focal point behind the mirror, as shown in Figure 11.3.6b.

To understand how a curved mirror produces an image, consider it to be made up of several tiny plane mirrors. A two-dimensional representation of this is shown in Figure 11.3.6. If parallel rays of light shine directly onto the surface of each mirror, the rays reflect and the angle of incidence equals the angle of reflection, therefore obeying the law of reflection for the position of the (plane) mirror it strikes.

Curved mirrors are usually spherical in shape as if the mirror has been made from a portion of a sphere. They are cheap and easy to manufacture but are only capable of bringing parallel light rays to an approximate focus. The reflected rays do not intersect at precisely the one single point, as shown in Figure 11.3.7a. This causes blurring of an image near the edges of the mirror. This distortion is called **spherical aberration** and is particularly noticeable if the mirror is large compared to its **radius of curvature**. If an undistorted image, free of spherical aberration, is required, a parabolic mirror is used. A parallel beam of light will reflect from a parabolic mirror to a sharp focus, as shown in Figure 11.3.7b.

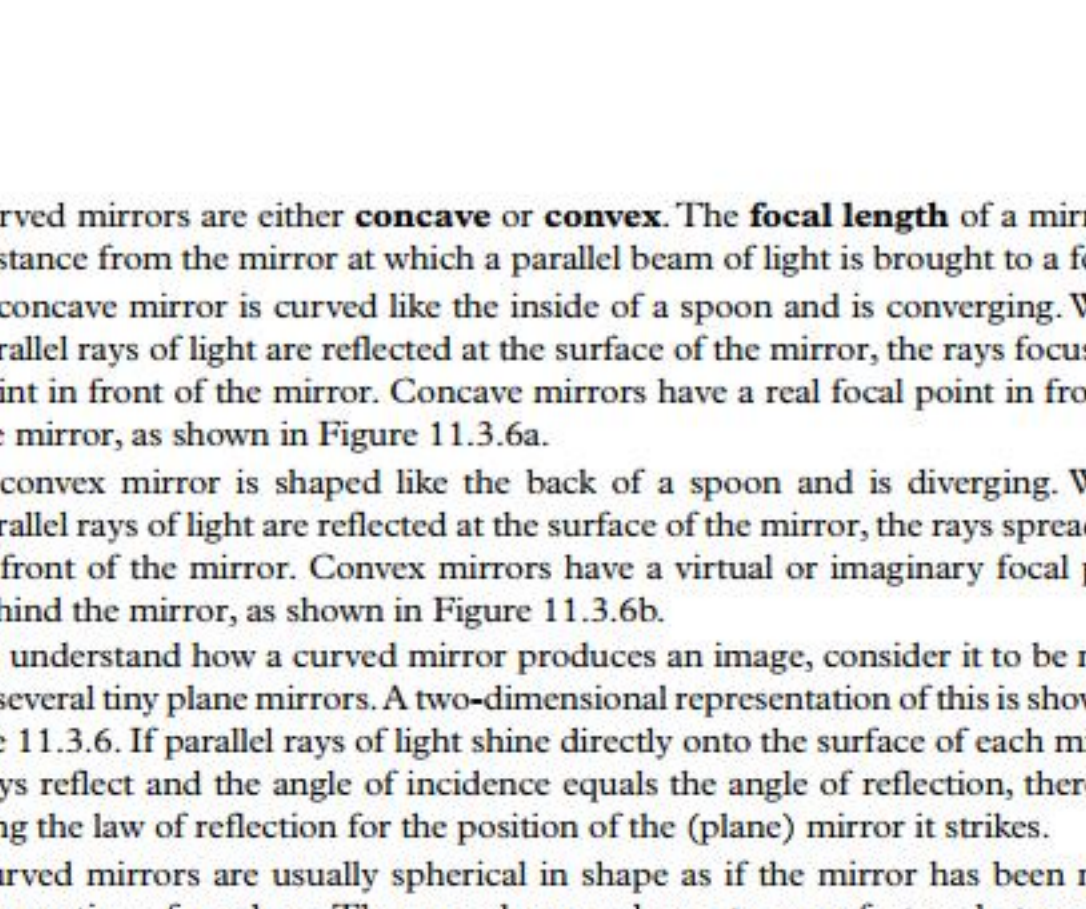


FIGURE 11.3.7 (a) Spherical mirrors do not have a precisely defined principal focus, and the further a ray of light is from the principal axis of the mirror, the greater the inaccuracy. The effect is most noticeable if the mirror is large compared to its radius of curvature. (b) A parabolic concave mirror will bring parallel rays to a perfect focus.

Spherical mirrors are often used in inexpensive torches and in security and dental mirrors, where the accuracy of the focal point is not a great concern. Parabolic mirrors are more difficult to produce and therefore are more expensive. Parabolic mirrors are usually reserved for situations in which a precise focus and undistorted images are required, such as in reflecting telescopes.

CONSTRUCTING RAY DIAGRAMS

The image in a spherical mirror or a lens can be found using a ray diagram. Before explaining how an image is found, some standard terms used to describe a spherical mirror, as shown in Figure 11.3.8, need to be defined.

- A vertical line called the optical axis represents the reflecting surface (the back of the mirror). Although the mirror surface is curved, the optical axis is a straight vertical line. A ray diagram tends to use a much larger vertical scale than horizontal scale, allowing the mirror to be represented by a straight line with little loss of accuracy.
- The optical axis is perpendicular to the **principal axis**, and the pole, P, the centre of the mirror, is placed at the intersection of the optical axis and the principal axis. A small, curved mirror symbol is placed here to indicate the type of mirror being used.
- The **principal focus** of the mirror, F, and its centre of curvature, C, are located on the principal axis to scale. The **centre of curvature** of the mirror is the point at the centre of the sphere of which the mirror forms a part.
- R is the radius of the sphere from which the mirror is assumed to have been made. This is the radius of curvature of the mirror.
- f is the distance between the pole and the principal focus. This is the focal length of the mirror. The focal length is half the radius of curvature: $f = \frac{R}{2}$
- Traditionally, the object is on the left of the optical axis, along with the eye that will view the image. The object is usually represented as a small vertical arrow.
- The distance from the object to the mirror (or optical axis) is called the object distance, u, and the distance from the optical axis to the image is the image distance, v, as shown in Figure 11.3.8b.

Use of these conventions is made to draw a ray diagram and find an image in a mirror (Figure 11.3.8b).

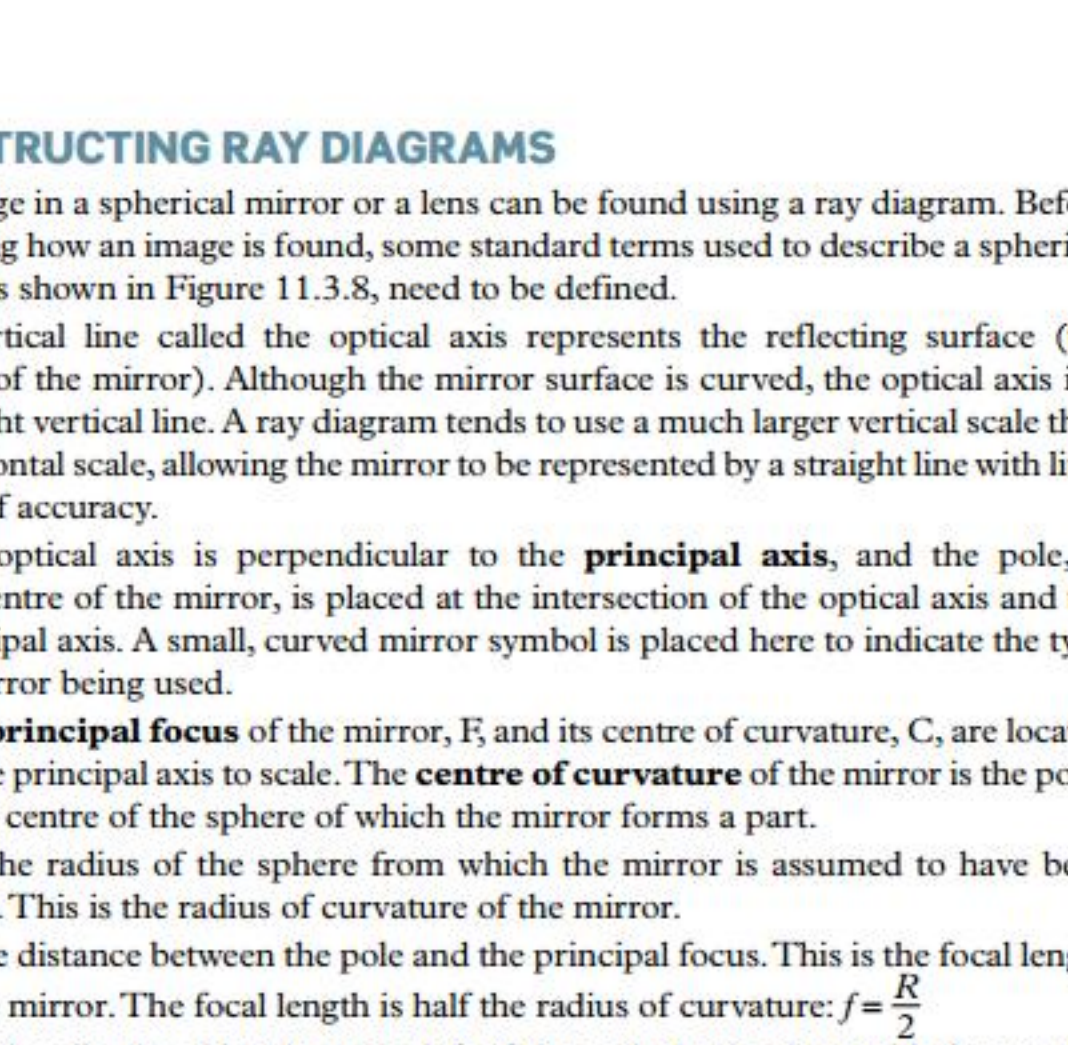


FIGURE 11.3.8 (a) Terminology used to describe spherical mirrors (b) Layout for a ray diagram to find the image of an object in a concave mirror

When constructing a ray diagram, the vertical scale for the diagram does not have to be the same as the horizontal scale. This is particularly useful if a tiny object such as a grain of rice is to be viewed in a mirror with a focal length of 20 cm. It is a good idea to use a third ray to check the final image. All three rays should meet at a single image point.

IMAGE FORMATION IN A CONCAVE MIRROR

To determine the image of an object in a concave mirror, the object is positioned on the principal axis to the left of the mirror. Between two and four rays are traced from the top of the object; the top of the image is found at the intersection of these rays. The rest of the image fills in the space from this point to the principal axis and is perpendicular to the principal axis. The four rays are described below and shown in Figure 11.3.9.

- Ray 1: A ray of light that travels parallel to the principal axis will be reflected through the principal focus of the mirror, as shown in Figure 11.3.9a.
- Ray 2: A ray of light emanating from the object and travelling through the centre of curvature of the mirror will strike the surface at an angle of 90°, along a normal. This ray will, therefore, be reflected along the path it came from, as shown in Figure 11.3.9b.
- Ray 3: The ray that strikes the pole of the mirror will reflect at an angle equal to the angle of incidence. At the pole, the mirror acts like a plane mirror and the principal axis becomes a normal, as shown in Figure 11.3.9c.
- Ray 4: The ray emanating from the object and travelling through the principal focus before striking the mirror will be reflected from the mirror parallel to the principal axis, as shown in Figure 11.3.9d.

If any two of these four rays are traced, the point at which they intersect determines the location and orientation of the image, as shown in Figure 11.3.9e. When the position of the image is found, you know that any ray emanating from the top of the object and striking the mirror must reflect through this point, and a clear image is produced.

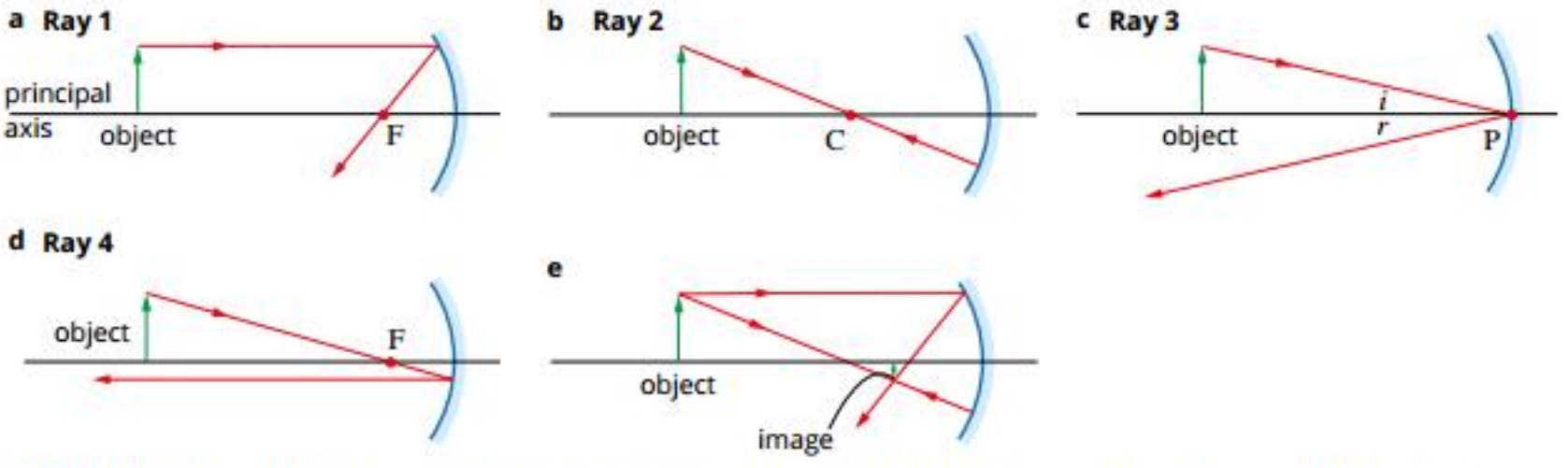


FIGURE 11.3.9 The path of four rays leaving the top of an object reflect from the mirror to produce an image. (a) This ray travels parallel to the principal axis and reflects through F. (b) Ray 2 passes through C and is reflected back along its incident path. (c) The ray striking the pole (P) will reflect as if it has struck a small plane mirror, $i = r$. (d) The ray passing through F reflects parallel to the principal axis. (e) Intersecting rays locate the image.

In practice, the quickest method to measure the focal length of a concave mirror is to stand near a window, holding the mirror so that an image of a distant object forms on a small white card or screen that you hold in your other hand. Light rays from a distant source are parallel to one another, so you are effectively focusing parallel rays of light. The distance from the mirror to the screen approximates the focal length of the mirror. Figure 11.3.10 shows the images produced when the same object is placed at various distances from a concave spherical mirror.

- Figure 11.3.10a shows that when an object is placed at a relatively large distance ($u > R$) from a concave mirror, the image formed is real, diminished and inverted.
- Figure 11.3.10b shows that when the object is placed at the centre of curvature of the mirror ($u = R$), the image formed is also real and inverted, but it is the same size and distance from the mirror as the object.
- Figure 11.3.10c shows that when the object is placed between the centre of curvature and the focal point ($f < u < R$), the image is again real and inverted, but now it is magnified.
- Figure 11.3.10d shows that when an object is placed at the principal focus of a concave mirror ($u = f$) the reflected rays will emerge parallel to one another. This is the arrangement used in car headlamps, torches and similar objects, in which a globe is placed at the focal point of a concave mirror. The rays leaving the top of the object strike the mirror and emerge parallel to one another so the image can be at infinity.
- Figure 11.3.10e shows that when an object is placed inside the focal length of the mirror ($u < f$), the reflected rays diverge like those from a plane mirror. This means that the rays cannot intersect to create a real image and the eyes interpret the diverging rays as coming from an image behind the mirror and a virtual, upright and magnified image results. The location of the image is found by extrapolating the rays back to their point of intersection, as shown. It is a virtual image, so it cannot be projected onto a screen.

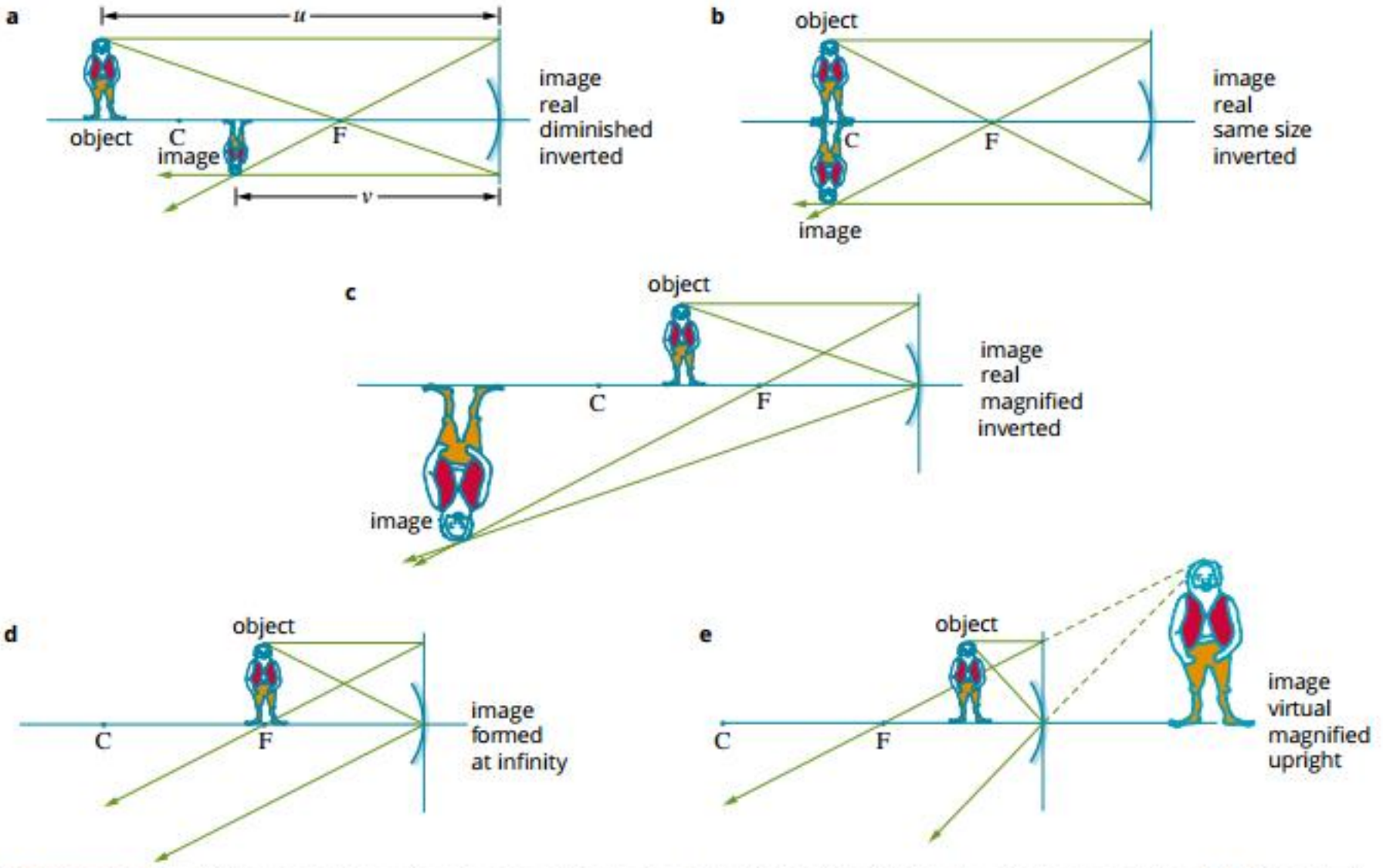


FIGURE 11.3.10 (a)–(c) A concave mirror will produce a real image when the object is placed farther than the focal point, F, and (d), (e) a virtual image when at or closer than the focal length.

The complete description of an image requires its nature (real or virtual), orientation (upright or inverted), position and magnification to be stated. Magnification refers to the size of an image relative to the object. If the image is larger than the object, it can be described as enlarged or magnified. A smaller image is described as diminished or reduced. Sometimes the actual height of an image must be found, so a carefully drawn scale diagram is essential.

The magnification, M, of an image is the factor by which the size of the object has been multiplied. This is the ratio of the height of the image to the height of the object. By convention, the height of an inverted image is assigned a negative value. A positive magnification value indicates that the image is upright relative to the object. A negative magnification value indicates that the image is inverted relative to the object.

- A magnified image has a magnification factor of greater than one, $|M| > 1$.
- A diminished image has a magnification factor of less than one, $|M| < 1$.
- If $|M| = 1$, the image and object are the same size.

A mirror producing a magnification of −1.2, for example, means that the image is inverted and 20% larger than the object.

Note that $|M|$ is the absolute value of M, which is the magnitude of the value regardless of the sign (positive or negative).

The magnification of an image in a mirror can also be found by the ratio of the image distance to the object distance. The ratio of the heights of the image and object is the same as the ratio of the distances of the image and the object from the mirror or lens.

The magnification factor in optics is the ratio of the image height to the object height and can be found by direct measurement of a scaled ray diagram or by the ratio of the image distance to the object distance.

A summary of the images formed by concave spherical mirrors is provided in Table 11.3.1.

TABLE 11.3.1 Summary of images formed by concave spherical mirrors

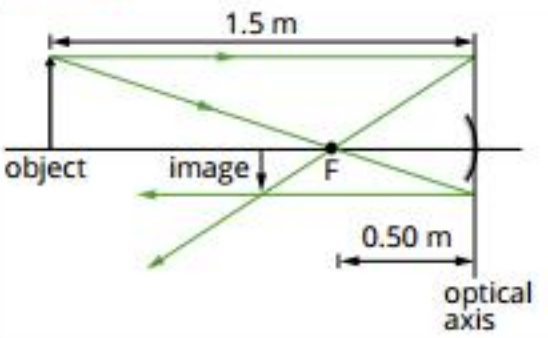
Position of object	Position of image	Description of image		
		Real or virtual	Upright or inverted	Enlarged or diminished
beyond C	between C and F	real	inverted	diminished
at C	at C	real	inverted	same size
between C and F	beyond C	real	Inverted	enlarged
at F	image at infinity	—	—	—
between F and P	behind mirror	virtual	upright	enlarged

Worked example 11.3.1

IMAGE FORMATION IN CONCAVE MIRRORS

An object is placed 1.5 m in front of a concave mirror with a focal length of 50.0 cm.

a Construct a ray diagram of this situation to describe the type of image formed.

Thinking	Working
Construct a ray diagram (only two rays are needed).	

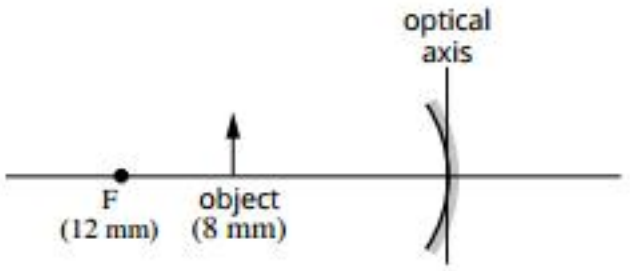
b Interpret the ray diagram.

Thinking	Working
Interpret the diagram. The image is in front of the mirror so it is real.	The image will be real, inverted and diminished.

➤ Try yourself 11.3.1

IMAGE FORMATION IN CONCAVE MIRRORS

A dentist holds a concave mirror of focal length 12 mm at a distance of 8 mm from the tooth that needs a filling.



a Construct a ray diagram of this situation to describe the type of image formed.

b Interpret the ray diagram.

IMAGE FORMATION IN CONVEX MIRRORS

Convex mirrors are common in everyday life. They are often used for security in the ceiling corners of shops and for traffic safety at blind corners—as shown in Figure 11.3.11—and as rear-view mirrors for long vehicles. Convex mirrors can be spherical, parabolic, ellipsoidal or hyperbolic in shape, the last three only being used in telescopes and other specialised equipment.

The reflecting surface of a spherical convex mirror is again a portion of a sphere, but in this case the reflective surface is on the outside of the sphere. Incident light rays parallel to the principal axis of a convex mirror will diverge on reflection. If the rays are drawn back behind the mirror, they appear to come from one single point. The virtual principal focus of the mirror is shown in Figure 11.3.12. The distance from the pole of the mirror to this point is the focal length of the mirror (f) and, as with a concave mirror, the focal length is half the radius of curvature:

$$f = \frac{R}{2}$$

Convex mirrors, like plane mirrors, can only produce a virtual image. A convex mirror always provides a wide field of view and an image that is always upright, as shown in Figure 11.3.13.

FIGURE 11.3.11 Convex mirrors are used on the road to help drivers view traffic around sharp corners.

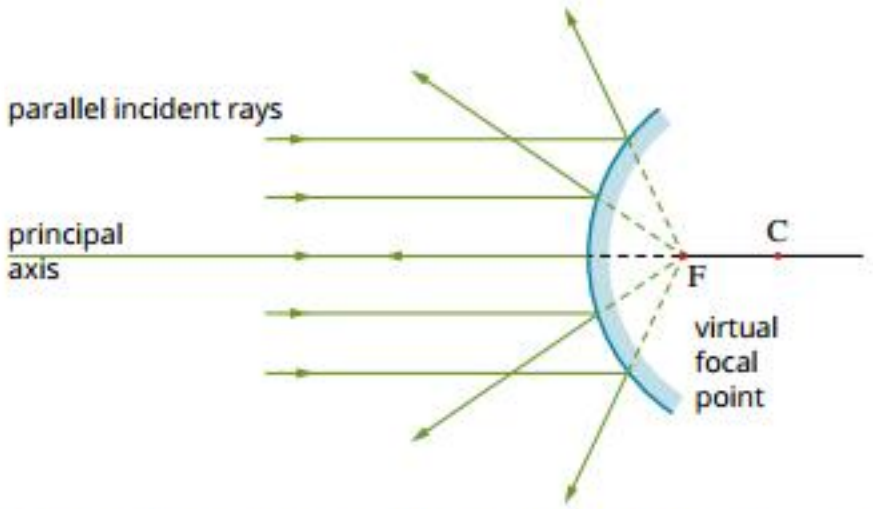


FIGURE 11.3.12 The parallel rays reflected from a convex mirror will diverge in such a way that they appear to come from a single point at a virtual focus. The reflecting surface is on the outside of the sphere indicated by the blue line.

When constructing a ray diagram for a convex mirror, the same conventions apply as for concave mirrors. A vertical line, the optical axis, representing the reflecting surface, is drawn perpendicular to the principal axis for the mirror. A small convex mirror symbol, whose pole lies at the origin for the axes, indicates the type of mirror used. The object is always placed to the left of the mirror and the principal focal point will lie to the right of the mirror (behind it). The horizontal and vertical scales need not be the same, so choose scales that accurately represent the height of the image.

Figure 11.3.13 shows the effect of placing the same object at various distances from a convex mirror. All the images lie behind the mirror between the pole and the focal point, and all are upright and diminished. Each image, however, has a different magnification that depends on the position of the object from the mirror. As the object is moved closer to the mirror, the image size increases. Because of the curvature of the mirror the image can never be quite as large as the object, so the absolute value of the magnification is always less than 1 ($|M| < 1$).

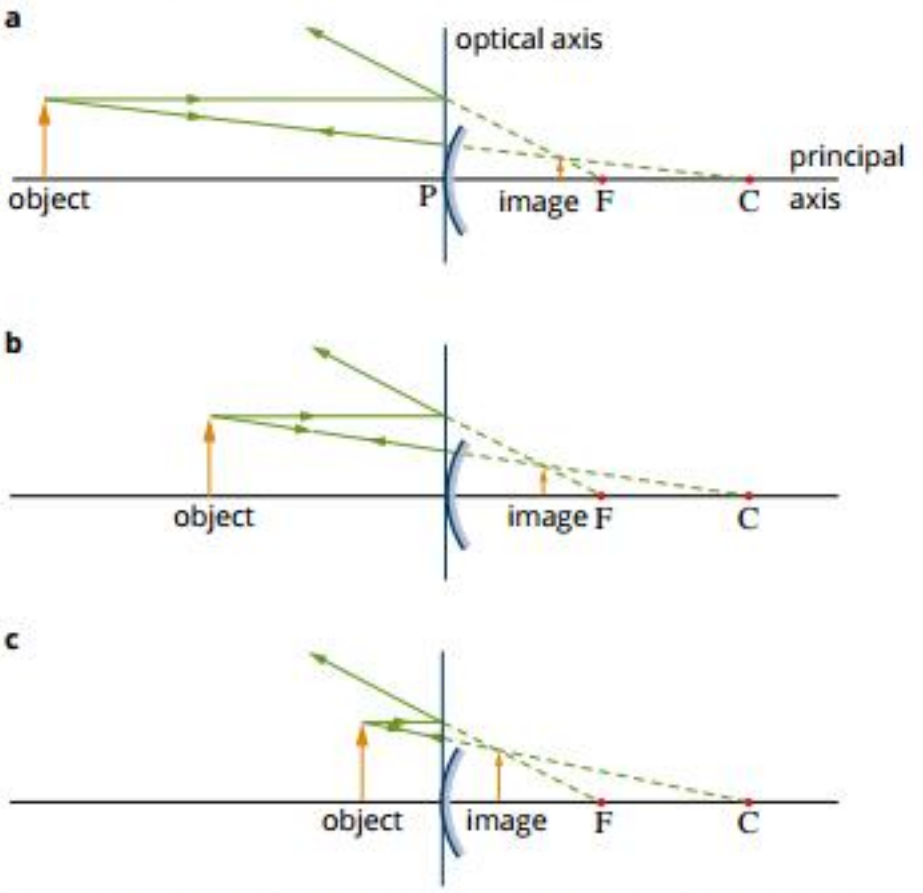


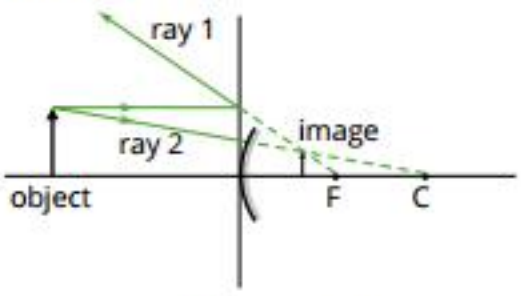
FIGURE 11.3.13 Ray tracing for a convex mirror. All images are upright, virtual and diminished. As the object is brought closer to the mirror, the image increases in size, but it will never be the same size as the object.

Worked example 11.3.2

IMAGE FORMATION IN CONVEX MIRRORS

A shop uses a convex mirror of focal length 2.0m for security purposes. A 1.5m tall person is standing 4.0m from the mirror.

Construct a ray diagram of this situation and describe the type of image formed.

Thinking	Working
Construct the ray diagram. (Only two rays are needed.)	
Interpret the ray diagram.	The image will be virtual, upright and diminished.

➤ Try yourself 11.3.2

IMAGE FORMATION IN CONVEX MIRRORS

An object is placed 30cm in front of a convex mirror of focal length 15cm.

Construct a ray diagram of this situation and describe the type of image formed.

11.3 Review

SUMMARY

- Ray-tracing can be constructed to determine the image formed by a mirror or lens. An image of a point exists when rays from the point converge (or appear to converge) at another point.
- There are four rays, incident on a curved mirror, whose paths can be predicted to determine the position, nature, orientation, size and magnification of the image. At least two rays must be traced to locate an image when constructing a ray diagram.
- The complete description of an image requires that the position, nature, orientation and size of the image be stated.
- Diverging rays of light entering the eyes are interpreted as having come from a single point behind a plane mirror, where a virtual image is seen.
- The nature of an image is either 'real' or 'virtual'. A real image is formed in front of the mirror and a virtual image is formed behind. The orientation of an image is either 'upright' or 'inverted' relative to the object.
- A plane mirror produces an image that is always virtual, upright and the same size.
- A curved mirror is usually spherical or parabolic in shape. Parabolic mirrors create more precise images but are more difficult and costly to produce.
- A concave mirror is curved like the inside of the bowl of a spoon. A convex mirror is curved like the back of a spoon.
- A concave mirror can produce real images that are inverted and virtual images that are upright, depending on the position of the object relative to the focal length.
- Rays parallel to the principal axis will diverge on reflection from a convex mirror. They reflect as if they come from a single point behind the mirror, the principal focus.
- A convex mirror is useful because it has a wide field of view and always produces upright images.
- The focal length of spherical concave and convex mirrors is half its radius of curvature: $f = \frac{R}{2}$
- Convex mirrors always produce images that are virtual, upright and diminished. The size of the image depends on how close the object is to the mirror, but the absolute value of the magnification is always less than 1.

KEY QUESTIONS

Describe

1 Describe the image that is formed by a plane mirror.

2 Describe the term 'radius of curvature' for a spherical mirror.

3 Construct a labelled diagram for the following on a spherical concave mirror: centre of curvature, principal axis, principal focus, pole, focal length, radius of curvature.

4 List the four characteristics that must be described for an image formed in a mirror. State the options for each characteristic.

Apply

5 There are some applications where a convex mirror will be used in preference to a plane mirror. Describe such an application. Explain the similarities and differences between the images produced.

6 How does the image of yourself in a plane mirror differ from a selfie photograph? Explain your answer.

Analyse

7 Contrast concave and convex mirrors. Name one application of each.

8 A cavity in a tooth is 2 mm long. A dentist uses a concave mirror of focal length 15 mm to view the tooth. The mirror is held 8 mm from the tooth. The length of the image is 17 mm. Describe the nature of the image formed.

9 A convex mirror of focal length 3 m is placed at a 'blind corner'. A person looking at the mirror sees a truck coming when the truck is 30 m from the mirror.
- **a** Describe the nature of the image.
- **b** Consider how the image of the truck will appear when it is 15 m from the mirror.

10 Explain the implication if a third reflected ray drawn on a ray diagram does not intersect with the first and second reflected rays in the same place.

11 Describe the image formed by a concave mirror when the object is placed between C and F.

11.4 Refraction of light and image formation with lenses

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- construct ray diagrams to demonstrate the refraction of light
- describe Snell's law
- use the wave model of light to explain refraction, total internal reflection and dispersion
- solve problems involving the refraction of light at the boundary between two mediums
- construct ray diagrams to determine image formation in single concave and convex lenses.

You will recall from Module 9.4 that light travels in a straight path through a uniform medium. But, when entering a medium with a different optical density, the light's path may be bent. Evidence of the bending of light is shown in Figure 11.4.1 in which a person's face can be seen through a glass of water. Some of the person's face can be seen directly. Light must be travelling along a straight path from the person's face to the observer's eyes. However, notice that parts of the person's face can also be seen through the glass of water. The light rays from the person's face passing through the glass of water have been re-directed or bent by the water towards the observer's eyes. The bending or change of direction of light as it passes from one medium to another is called refraction.

A number of common phenomena are caused by refraction, including the break that appears in a straw that is standing in a glass of water, as shown in Figure 11.4.2.

Refraction is the bending of the path of light due to a change in speed as it enters a medium of different optical density.

FIGURE 11.4.1 Refraction occurs because the light changes speed as it enters a medium of different optical density. In this case, the light reflected from the person's face is bent as it enters and leaves the glass of water. As a result the face is seen 'inside' the glass of water.

FIGURE 11.4.2 The refraction of light makes the straw appear to have a break in it.

To fully understand these phenomena, the refraction of light can be investigated by using a block of glass and a narrow beam of light. Figure 11.4.3 shows a light beam travelling through air and entering a semicircular glass block. When light strikes the surface of a material, some of the incident light is reflected, some is transmitted, and some is absorbed by the material. The transmitted ray deviates from its original direction of travel. This change in direction occurs at the boundary between the air and the glass; the ray has been refracted. Refraction occurs because the light changes speed as it enters a medium of different optical density.

FIGURE 11.4.3 A light ray strikes the surface of a glass prism at an angle of incidence of 90° and is transmitted through the prism. The transmitted ray is refracted as it leaves the prism because of a change in the speed of the light. The bending occurs at the boundary of the two media.

REFRACTION BY RAYS

The refraction of light can be represented using a ray approach. The ray of light that strikes the boundary between two media is called the incident ray. A normal to the boundary is drawn at 90° to the boundary at the point where the incident ray strikes. The angle between the normal and the incident ray is called the angle of incidence, i. The angle between the normal and the transmitted or refracted ray is called the angle of refraction, r. The incident ray, the normal and the refracted ray all lie in the same plane, as shown in Figure 11.4.4.

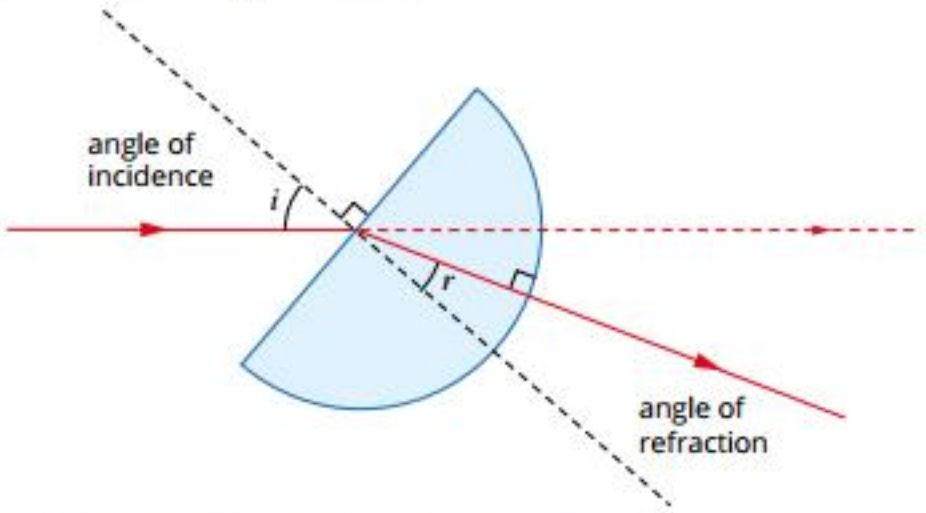


FIGURE 11.4.4 The angles of incidence and refraction are defined as shown above. An example of refraction can be seen as light enters the glass prism.

Refraction is only noticeable if the angle of incidence is larger than 0°. If the incident ray is perpendicular to the boundary (that is, if $i = 0$), the direction of travel of the transmitted ray will not deviate even though the speed of light has altered. This can be seen in Figure 11.4.4 as the ray leaves the prism and continues in a straight path, and in Figure 11.4.3 where the light enters the prism and continues in a straight line through the glass.

When light travelling through air enters a more optically dense medium such as glass (where it travels more slowly), it will be refracted so that the angle of refraction is smaller than the angle of incidence. The path of light has been deviated 'towards the normal'. When light passes from glass to air it speeds up, as it has entered a less optically dense medium. The angle of refraction will be larger than the angle of incidence. The path of light has refracted 'away from the normal'.

The behaviour of light undergoing refraction can be summarised by two statements:

- When a light ray passes into a medium in which it travels more slowly (a more optically dense medium), it is refracted towards the normal.
- When a light ray passes into a medium in which it travels faster (a less optically dense medium), it is refracted away from the normal.

REFRACTION BY WAVES

Although the way in which light is reflected is modelled equally effectively using either a particle or wave approach, this is not the case for refraction. The wave model is better able to explain the change in direction that is observed as light enters a medium in which its speed is altered.

Consider a light wave travelling at an angle towards a boundary between two media of differing optical density; for example, air to water, as shown in Figure 11.4.5a. As soon as the light wave enters the water it will slow down. At the moment shown in the diagram, the section of wavefront, AB, that first enters the water will be travelling at a slower speed than the section of the same wavefront, BC, that has not yet entered the water. This first section of the wavefront then effectively lags behind the position that it would have held had it continued at its initial faster speed. The overall result of this delay is that the direction of travel of the overall wavefront is altered. Figure 11.4.5b shows that, once several wavefronts have passed into the second medium, the direction of travel of the overall wave is deviated from its original course. A similar arrangement can be constructed for the refraction of light as it speeds up.

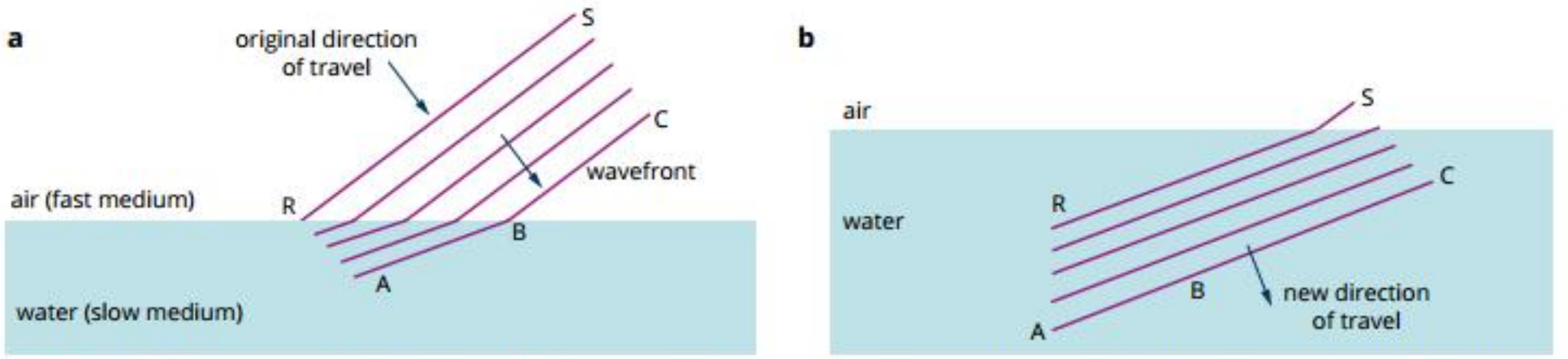


FIGURE 11.4.5 The change in the direction of light that is associated with a change of speed is called refraction. Refraction can be modelled by treating light as a wave.

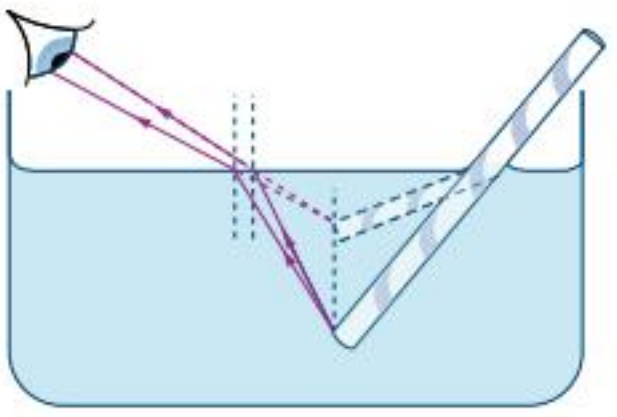


FIGURE 11.4.6 The immersed portion of the straw is apparently shifted upwards due to refraction. This is because the rays appear to have come from a raised position in the glass of water.

Objects partially immersed in water will be distorted because of refraction and will appear to have a kink. This is shown clearly in the photograph of the straw in Figure 11.4.2, page 436. The path of the rays that produce this illusion can be drawn using a ray diagram, as shown in Figure 11.4.6. As each ray of light emitted from the base of the straw encounters the water–air boundary, it is refracted away from the normal, because the ray enters the less optically dense air. The observer perceives these rays from the base of the straw to have come from a position higher up in the glass of water. Ray tracing can be carried out for each point along the straw, resulting in the image shown. The straw appears to have a bend in it because the part of the straw that is submerged appears closer to the air–water boundary than it actually is.

Note that although ray diagrams are commonly used to represent the refraction of light and the formation of images in mirrors and lenses, these describe only the direction of travel of the refracted light and do not tell the whole story. Wave diagrams are more complicated but show the reasons for the change in direction of travel of the light.

THE LAW OF REFRACTION: SNELL'S LAW

In about 1621, Dutch scientist Willebrord Snell found that, for a given pair of media, the sine of the angle of incidence was directly proportional to the sine of the angle of refraction. This relationship is now known as **Snell's law**.

$$\sin i \propto \sin r$$

$$\frac{\sin i}{\sin r} = \text{constant}$$

Each combination of a pair of materials has a different constant value. For example, the constant for the air–water interface is different from that for the glass–water interface. The constant is called the **relative refractive index**, denoted by the symbol n.

Different transparent media allow light to travel at different speeds. Light travels fastest in a vacuum, more slowly in water and even more slowly in glass, which is more optically dense than water.

Table 11.4.1 shows the speed of light in various media. The amount of refraction occurring at any boundary depends upon the extent to which the speed of light changes between the media.

TABLE 11.4.1 The speed of light in different media for yellow light ($\lambda = 589\,\text{nm}$)

Material	Speed of light ($\times 10^8\,\text{m s}^{-1}$)
vacuum	3.00
air	3.00
ice	2.29
water	2.25
quartz	2.05
crown glass	1.97
flint glass	1.85
diamond	1.24

Snell's law can be expressed in terms of the ratio of the two speeds of light in the two different media, v_1 and v_2, as shown in Figure 11.4.7.

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2}$$

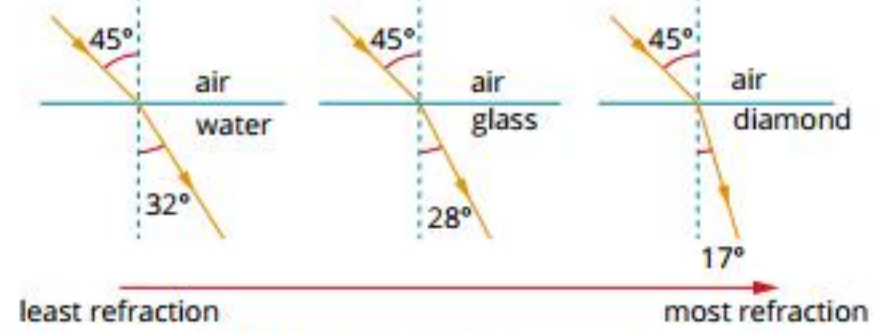


FIGURE 11.4.7 In each case, light is entering a medium of greater optical density. The bending of the path of the light depends on the ratio of the speeds in the two different media. The path of light deviates most when the change in speed is greatest.

> **i** The greater the change in the speed of a light ray passing through the boundary of different media, the greater the deviation of the ray.

THE INDEX OF REFRACTION

The degree of refraction is determined by comparing the speeds of light in the two different media. The **absolute refractive index**, n, of a medium is the ratio of the speed of light in the medium, v_{medium}, to the speed of light in a vacuum, c. Note that the term 'absolute refractive index' is often abbreviated to 'refractive index'.

$$n = \frac{c}{v_{\text{medium}}}$$

By definition, the refractive index of a vacuum would be exactly 1. Light travels only marginally more slowly in air and so the refractive index of air is 1.0003, but in most cases a value of 1.00 is sufficiently accurate. Materials in which light travels slowest will have the highest indices of refraction. For example, if a particular medium allowed light to travel at half the speed it does in a vacuum, then the refractive index of the medium would be 2.

The refractive index can therefore be considered an indication of the 'bending power' of a material. Table 11.4.2 lists the absolute refractive indices for various media.

TABLE 11.4.2 The refractive index of light in different media for yellow light ($\lambda = 589\,nm$)

Material	Refractive index, n
vacuum	1.00
air	1.00
ice	1.31
water	1.33
quartz	1.46
crown glass	1.52
flint glass	1.62
diamond	2.42

Snell's law can then be expressed in terms of the ratios of the speed of light in each medium v_1 and v_2, the wavelengths in each medium λ_1 and λ_2 and the absolute refractive indices of the respective mediums n_1 and n_2:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

Note that the wavelength of the light will vary with the change in speed but the frequency and, therefore, the colour remain unchanged. Since frequency is the number of waves passing a given point per second, it must remain constant. Extra waves cannot appear or disappear.

Snell's law:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

where

- i is the angle of incidence
- r is the angle of refraction
- v_1 is the speed of light in medium 1
- v_2 is the speed of light in medium 2
- λ_1 is the wavelength of the light in medium 1
- λ_2 is the wavelength of the light in medium 2
- n_1 is the refractive index of medium 1
- n_2 is the refractive index of medium 2.

Worked example 11.4.1

CALCULATING REFRACTIVE INDEX

The speed of light in water is $2.25 \times 10^8\,m\,s^{-1}$. Calculate the refractive index of water given that the speed of light in a vacuum is $3.00 \times 10^8\,m\,s^{-1}$.

Thinking	Working
Recall the definition for refractive index.	$n = \frac{c}{v_{medium}}$
Substitute the appropriate values into the formula and solve.	$n = \frac{3.00 \times 10^8}{2.25 \times 10^8} = \frac{3.00}{2.25} = 1.33$ The refractive index of water is 1.33.

➤ Try yourself 11.4.1

CALCULATING REFRACTIVE INDEX

The speed of light in crown glass (a type of glass used in optics) is $1.97 \times 10^8\,m\,s^{-1}$. Calculate the refractive index of crown glass given that the speed of light in a vacuum is $3.00 \times 10^8\,m\,s^{-1}$.

Worked example 11.4.2

SPEED OF LIGHT CHANGES

A ray of light travels from crown glass ($n = 1.52$), where it has a speed of $1.97 \times 10^8 \text{ m s}^{-1}$ into water ($n = 1.33$). Calculate the speed of light in water.

Thinking	Working
Recall the relevant part of Snell's law.	$\frac{v_1}{v_2} = \frac{n_2}{n_1}$
Substitute the appropriate values into the formula and solve.	$\frac{1.97 \times 10^8}{v_2} = \frac{1.33}{1.52}$ $1.33 \times v_2 = 1.52 \times 1.97 \times 10^8$ $v_2 = \frac{1.52 \times 1.97 \times 10^8}{1.33}$ $= 2.25 \times 10^8 \text{ m s}^{-1}$

➤ Try yourself 11.4.2

SPEED OF LIGHT CHANGES

A ray of light travels from water ($n = 1.33$), where it has a speed of $2.25 \times 10^8 \text{ m s}^{-1}$, into glass ($n = 1.85$). Calculate the speed of light in glass.

Worked example 11.4.3

USING SNELL'S LAW

A ray of light in air strikes the surface of a pool of water ($n = 1.33$) at angle of 30.0° to the normal. Calculate the angle of refraction of the light in water.

Thinking	Working
Recall the relevant part of Snell's law.	$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$
Recall the refractive index of air.	$n_1 = 1.00$
Substitute the appropriate values into the formula to find a value for $\sin r$.	$\frac{\sin 30°}{\sin r} = \frac{1.33}{1.00}$ $1.00 \times \sin 30° = 1.33 \times \sin r$ $\sin r = \frac{1.00 \times \sin 30°}{1.33}$ $= 0.3759$
Calculate the angle of refraction.	$r = \sin^{-1}(0.3759) = 22.1°$

➤ Try yourself 11.4.3

USING SNELL'S LAW

A ray of light in air strikes a piece of flint glass ($n = 1.62$) at an angle of incidence of 50.0° to the normal. Calculate the angle of refraction of the light in the glass.

- As the angle of incidence is increased, the angle of refraction also increases.
- If the angle of incidence is the critical angle, i_c, then the angle of refraction will be 90° and the light will be transmitted along the surface of the incident medium.
- If the angle of incidence is greater than the critical angle, then the angle of refraction will be greater than 90° and all of the light will be reflected and none will be transmitted.

The critical angle for any boundary between two media:

$$\sin i_c = \frac{n_2}{n_1}$$

where

i_c is the critical angle as light is transmitted into a medium n_2

n_1 is the refractive index of medium 1

n_2 is the refractive index of medium 2

light has a greater speed in medium n_2 than the medium n_1.

TOTAL INTERNAL REFLECTION AND CRITICAL ANGLE

Recall that, when light travels from water into air, the transmitted light enters a less optically dense medium, so it travels faster and is refracted away from the normal. The series of diagrams in Figure 11.4.8 show the effects of increasing the angle of incidence on light transmitted between these two media.

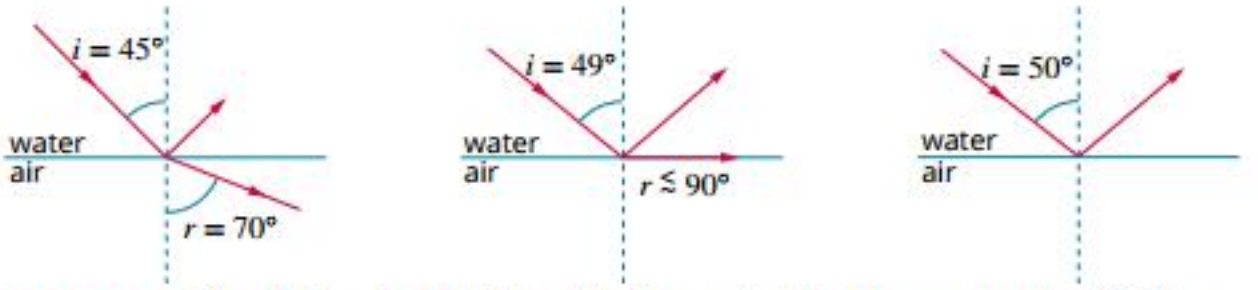


FIGURE 11.4.8 The critical angle for light travelling from water into air is approximately 49°. If the incident angle is greater than 49° total internal reflection occurs.

As the angle of incidence is increased, the angle of refraction also increases. This continues until, at a certain angle of incidence called the **critical angle**, i_c, the angle of refraction will be 90° and the transmitted ray travels just along the surface of the water. The angle of refraction can increase no further. If the angle of incidence is then increased beyond the critical angle, then no light is transmitted, and **total internal reflection** will occur. The critical angle is appropriately named, because none of the incident light energy can be transmitted into the next medium. In effect, as the angle of incidence increases, all of the light is reflected and no light is transmitted.

The critical angle can be found for any boundary between two media by using Snell's law. If the refractive indices of the two media are known, assuming that the angle of refraction is 90°, then the critical (incident) angle can be calculated:

$$\frac{\sin i_c}{\sin 90} = \frac{n_2}{n_1}$$

$$\frac{\sin i_c}{1} = \frac{n_2}{n_1} \qquad (\sin 90° = 1)$$

$$\sin i_c = \frac{n_2}{n_1}$$

Worked example 11.4.4

CALCULATING CRITICAL ANGLE

Calculate the critical angle for light passing from water into air.	
Thinking	**Working**
Recall the equation for critical angle.	$\sin i_c = \frac{n_2}{n_1}$
Substitute the refractive indices of water and air into the formula. (Unless otherwise stated, assume that the second medium is air with $n_2 = 1$.)	$\sin i_c = \frac{1.00}{1.33} = 0.7519$
Solve for i_c.	$i_c = \sin^{-1}(0.7519) = 48.8°$

➤ Try yourself 11.4.4

CALCULATING CRITICAL ANGLE

Calculate the critical angle for light passing from diamond into air.

The refractive index of any given medium depends on the colour (wavelength or frequency) of the light travelling through the medium, so each colour of light will have a slightly different critical angle. For example, if the critical angle for red light travelling from glass to air is 40.5°, then yellow light would have a slightly smaller critical angle of 40.2°. Violet light would have an even smaller critical angle of 39.6°. Although these values are very similar, they are sufficiently different to cause the dispersion of white light into the various colours of the rainbow.

Dispersion occurs when white light is split into its composite colours (red, orange, yellow, green, blue and violet). This can be demonstrated by shining a beam of white light into a triangular prism at an angle that causes the spectrum of colours to become visible, as shown in Figure 11.4.9. The spectrum occurs because each colour has a different refractive index. The refractive indices for violet light ($n = 1.53$) and red light ($n = 1.51$) in crown glass vary fractionally, but enough to bend the colours by slightly different amounts. The violet light waves are, therefore, refracted more than the red light waves. When the waves emerge from the glass into the air, they are refracted a second time by different amounts and separate further.

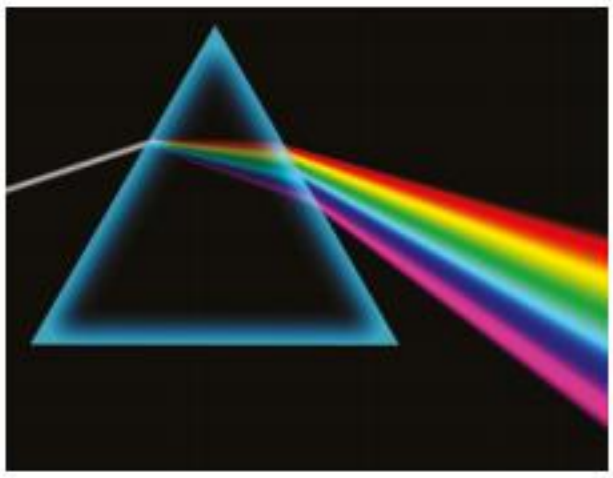


FIGURE 11.4.9 White light is refracted on entering and exiting a triangular prism. At both faces the coloured light waves are refracted by different amounts because each colour has a different refractive index. This effectively separates the colours.

The formation of rainbows, as shown in Figure 11.4.10, incorporates three different light wave phenomena that occur when sunlight encounters rain droplets in the air. As the light passes into the droplets of water, refraction, total internal reflection and dispersion take place, causing an image of the colours to appear in the sky.

Diamond has a very high refractive index, so it has a small critical angle. This means that a light ray that enters a diamond will often bounce around inside the diamond many times before leaving it. This causes the diamond to 'sparkle' as it appears to reflect more light than is falling on it. A jeweller can cut a diamond to take advantage of this property, as shown in Figure 11.4.11.

FIGURE 11.4.10 Rainbows form when sunlight shines through raindrops, which have a higher refractive index than air.

FIGURE 11.4.11 The refractive properties of diamonds mean they appear to sparkle.

REFRACTION AND LENSES

In the preceding sections you have seen how ray tracing can be used to demonstrate the formation of images by plane and curved mirrors, and in tracing the path of refracted light. A similar approach can be taken with images formed by lenses.

A **lens** is a piece of transparent material that has been shaped so that the light passing through it will bend in a particular way. Lenses can take on a variety of shapes, depending on the optical properties required of them.

The function of a lens can be demonstrated by examining the refraction of light rays as they change speed on entering and exiting a lens. Refraction must occur as the light both enters and exits the lens, so the curvature of both surfaces of the lens must be chosen specifically for a particular application. The curvature of the surface of most lenses is spherical and the surface of the lens is a portion of a sphere. Spherical lenses do have some problems related to accurate image formation but are very commonly used. Spherical lenses are much easier and cheaper to produce than other shapes, so non-spherical lenses are generally only used in high precision optical equipment.

This section covers bi-concave or bi-convex lenses, which are the most common types of spherical lenses. Scientists often just call these 'concave' and 'convex' lenses respectively.

- Convex lenses have one or both sides curved outwardly, like the back of a spoon. These are called plano-convex and bi-convex respectively, as shown in Figure 11.4.12a on the next page.
- Concave lenses have one or both surfaces curved inwardly like the bowl of a spoon. These are called plano-concave and bi-concave respectively, as shown in Figure 11.4.12b on the next page.

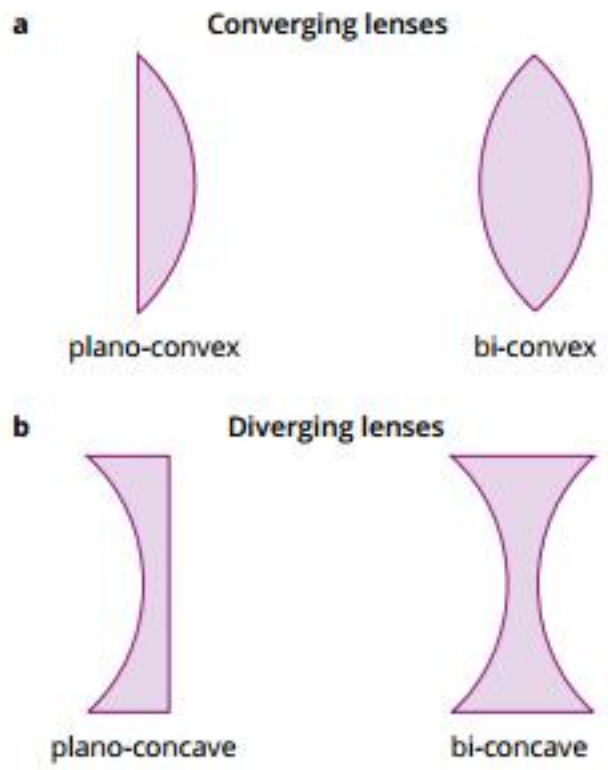


FIGURE 11.4.12 (a) Converging lenses are convex lenses, which are thicker in the middle. (b) Diverging lenses are concave lenses, which are thinner in the middle. In both types of spherical lenses, the curved surfaces form part of the surface of a sphere.

Figure 11.4.13 demonstrates the effects that convex and concave lenses have on a beam of light. The path of light is bent at the front and back surfaces of the lens, according to the law of refraction. The shapes of these lenses have been chosen so that the separate light rays converge to a single point.

- Figure 11.4.13a shows a convex lens. Rays parallel to the principal axis enter a convex lens and converge to the principal focal point or focus, F, of the lens.
- Figure 11.4.13b shows a concave lens. The curvature of the faces means that parallel rays diverge after passing through the lens. The diverging rays can be traced back through the lens to a point behind the lens. This is the principal focal point for a concave lens. It is sometimes known as a virtual focus because the rays do not meet at this point in reality. A virtual image formed by a lens can only be seen when looking directly through the lens.

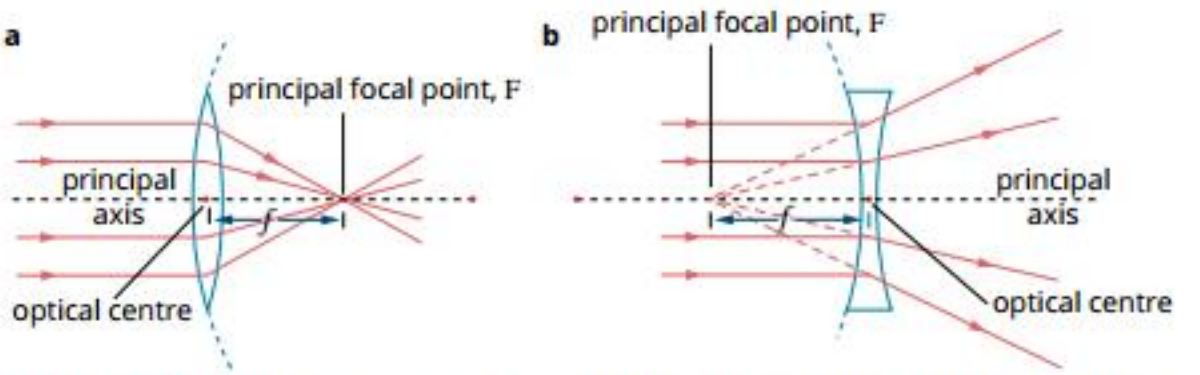


FIGURE 11.4.13 (a) For a convex lens, rays parallel to the principal axis converge to the principal focal point. (b) For a concave lens, rays parallel to the principal axis diverge as if they came from a single principal focal point called the virtual focus. Note that, for simplicity, the rays are shown bending from the optical axis of each lens. In reality the light waves bend on entering and exiting each lens.

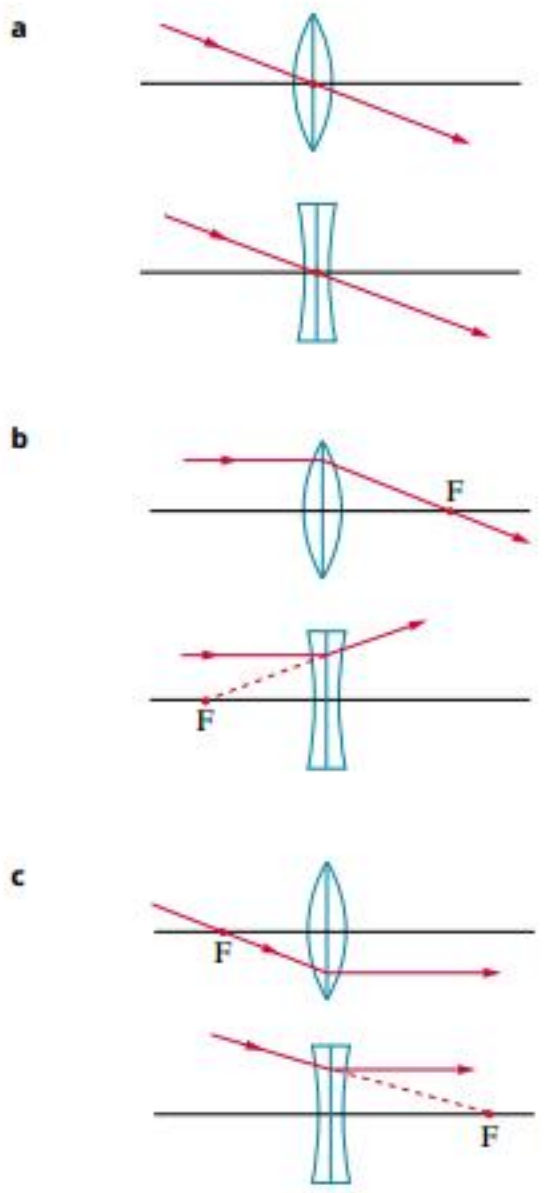


FIGURE 11.4.14 (a) A ray passing through the optical centre is undeviated. (b) A ray parallel to the principal axis passes (or appears to pass) through the principal focal point, F. (c) A ray that passes through (or travels towards) the focal point emerges parallel to the principal axis.

Each lens is considered to have two focal points (or foci), one either side of the lens. Each lens also has a special point known as the optical centre of the lens. A light ray that passes through the optical centre of the lens experiences no refraction; it passes straight through the lens undeviated (it does not bend). The distance between the optical centre and the focal point is known as the focal length (f) of the lens. As with mirrors, it is helpful to imagine the principal axis of the lens as a line that passes through the two focal points and the optical centre.

RAY PATHS THROUGH SPHERICAL LENSES

The nature of the image formed by either a concave or a convex spherical lens can be determined using the ray tracing techniques shown previously in Module 11.3. For spherical lenses there are three particular rays whose path can be predicted, and any two of these rays can be used to locate the image, as shown in Figure 11.4.14. A third ray can then be drawn to verify the final image.

- Figure 11.4.14a shows that a ray passing through the optical centre of a spherical lens will be undeviated.
- Figure 11.4.14b shows that a ray travelling parallel to the principal axis will be deviated through the principal focus of a convex lens, or deviated so that it appears to have come from the principal focus of a concave lens.
- Figure 11.4.14c shows that a ray passing through the principal focus of a convex lens (or directed towards the principal focus of a concave lens) will be deviated so that it emerges parallel to the principal axis.

Graphical ray tracing can also be used to locate the image formed by a spherical lens. A horizontal line represents the principal axis for the lens. A vertical line called the optical axis represents the lens. To indicate the type of lens in use, a small symbol is drawn at the intersection of the principal and optical axes. The principal foci of the lens should be labelled. All refraction is shown as occurring at the optical axis.

There are four aspects of an image that may be determined.

- nature: whether the image is real or virtual
- orientation: whether the image is upright or inverted
- position: the distance of the image from the optical axis
- size: the image is described as enlarged, reduced or the same size as the object.

Figures 11.4.15 and 11.4.16 demonstrate how ray diagrams can be used to locate the images of objects at various distances from concave and convex lenses respectively. Figure 11.4.17 shows how a concave lens always shows a virtual, reduced, upright image.

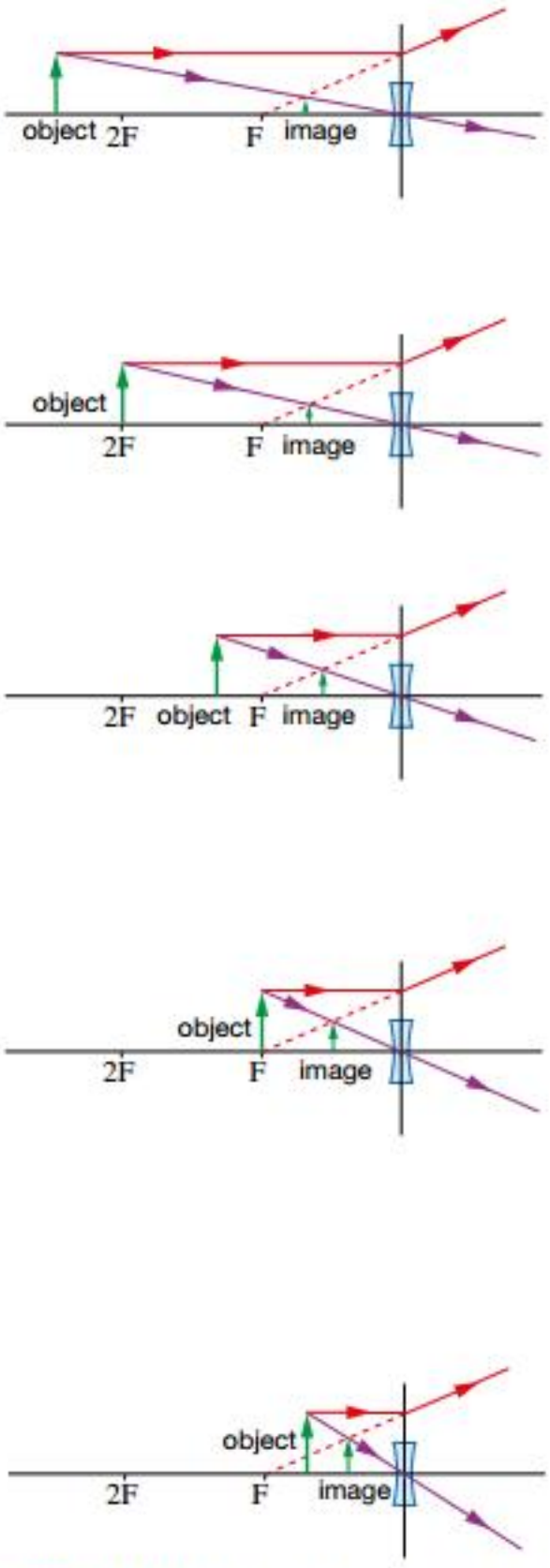


FIGURE 11.4.15 A concave lens causes rays to diverge and so a virtual, reduced image is always formed regardless of where the object is in relation to the lens.

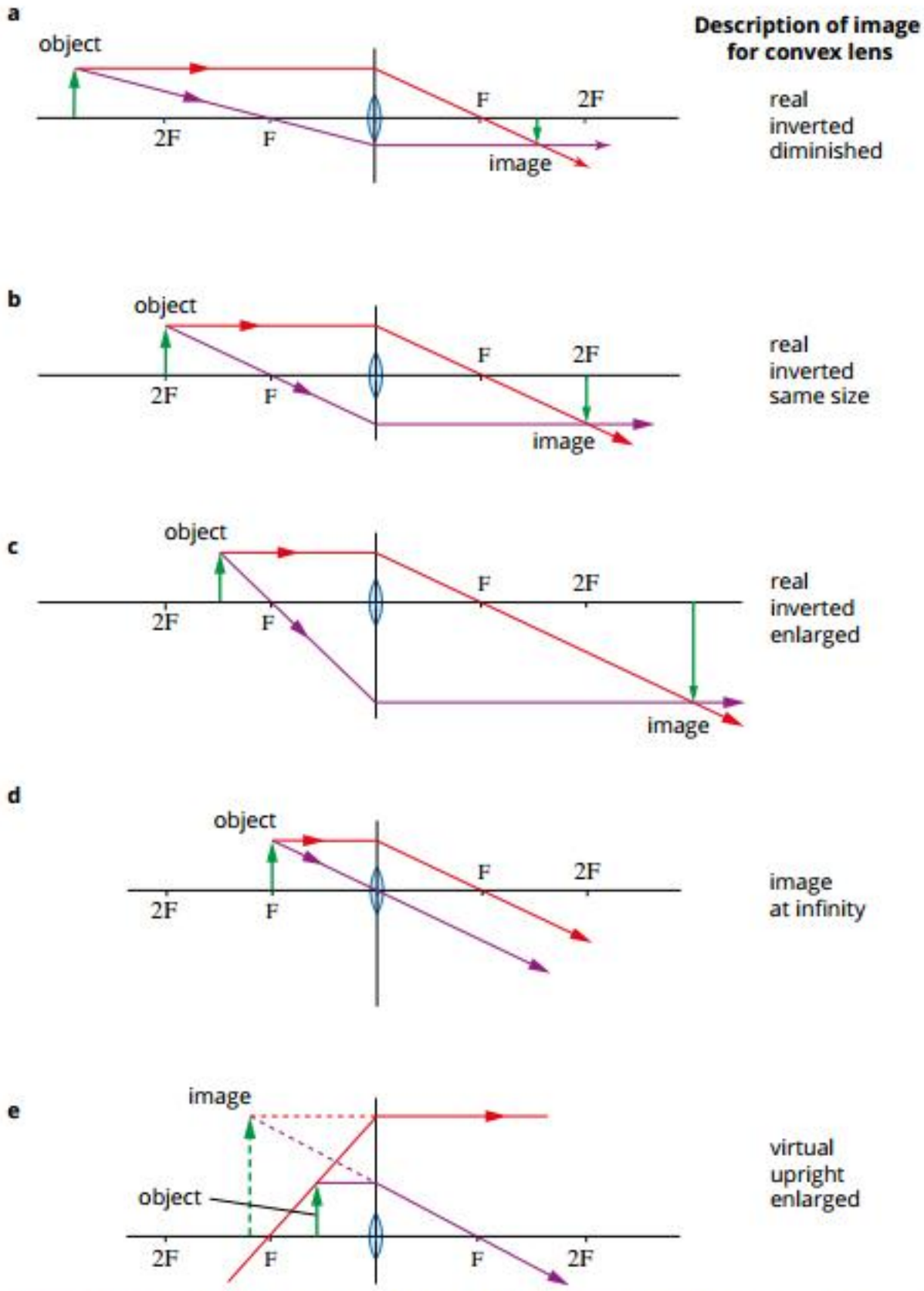


FIGURE 11.4.16 (a)–(c) When the object is placed beyond the focal point of a convex lens, a real image is formed. As the object is brought closer, the size of the image increases. (d) The image of an object at the focal point of a convex lens is considered to be at infinity. (e) A convex lens forms an upright, virtual image of an object placed inside the focal point.

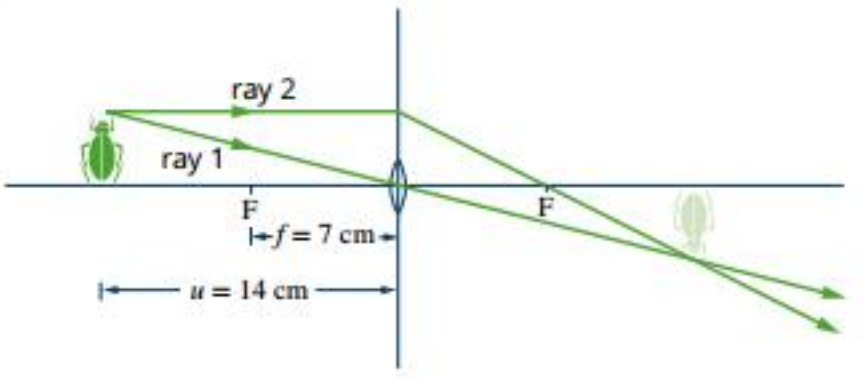
FIGURE 11.4.17 A concave lens always forms a reduced upright image.

Worked example 11.4.5

USING LENSES

A child examines a beetle by using a magnifying glass (a convex lens) of focal length 7 cm and holding the magnifying glass 14 cm from the beetle.

Construct a ray diagram to describe the image.

Thinking	Working
Construct the ray diagram (only two rays are needed).	
Interpret the ray diagram.	The image is virtual, inverted and the same size as the object.

➤ Try yourself 11.4.5

USING LENSES

An artist uses a concave lens of focal length 10 cm to reduce a sketch of a tree to see what it would look like in miniature. The sketch is of a 20 cm tall tree and the lens is held 15 cm above the page.

Construct a ray diagram to describe the image.

11.4 Review

SUMMARY

- Refraction is the bending of light due to a change in its speed as it enters a medium of different optical density. The greater the change in the speed of light, the greater the bending.
- The angle between the normal and the incident ray is called the angle of incidence. The angle between the normal and the transmitted or refracted ray is called the angle of refraction.
- When a light ray passes into a medium in which it travels more slowly (a more optically dense medium) it is refracted towards the normal.
- When a light ray passes into a medium in which it travels faster (less optically dense) it is refracted away from the normal.
- A transparent medium has an absolute refractive index, n, determined by the speed at which light can travel in the medium compared with the speed of light in a vacuum, c:

$$n = \frac{c}{v_{medium}}$$

where c is the speed of light in a vacuum and v_{medium} is the speed of light in the medium.

- Snell's law describes the relationship between the angle of incidence, i, and the angle of refraction, r, for a given pair of media:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

- As the angle of incidence of light onto a transparent surface is increased, proportionally more light is reflected and less light is refracted.
- When light enters a less optically dense medium it is refracted away from the normal. At the critical angle, i_c, the angle of refraction is 90°.
- If the incident angle is greater than the critical angle, i_c, total internal reflection occurs.
- The critical angle is given by:

$$\sin i_c = \frac{n_2}{n_1}$$

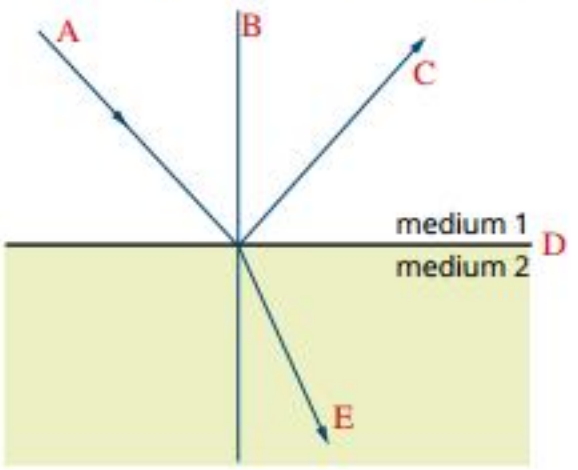
- The path of light is refracted as light both enters and exits a lens. A convex or converging lens brings parallel rays to a focus. A concave or diverging lens spreads parallel rays further apart.
- For spherical convex and concave lenses there are three rays whose paths can be predicted easily, and any two of these rays can be used to locate an image.
  - Ray 1: A ray through the optical centre is undeviated.
  - Ray 2: A ray parallel to the principal axis passes (or appears to pass) through the principal focus.
  - Ray 3: A ray through (or travelling towards) the principal focus emerges parallel to the principal axis.
- Graphical ray tracing can be used to locate the image formed by a spherical convex lens. The nature, orientation, position and size of the image depends on the position of the object relative to the focal length of the lens.
- In general, convex lenses form real images of distant objects and virtual images of very close objects.
- Regardless of the position of the object, a concave lens always forms a virtual, upright and diminished image. The image is always on the same side of the lens as the object. When the object is brought closer to the lens the image becomes larger, but it can never equal the size of the object.

11.4 Review *continued*

KEY QUESTIONS

Describe

1 The figure below represents a situation involving the refraction of light. Complete the following table with the letter corresponding to each line on the diagram.



boundary between two media	
normal	
incident ray	
refracted ray	
reflected ray	

2 State the direction in which light bends when a light ray passes into a medium in which it travels more slowly (a more optically dense medium).

3 Describe what happens to the path of parallel rays of light passing through a convex lens.

Apply

4 Explain why an upright, real image can never be formed by a single concave lens.

5 Why do light waves travelling along the normal not bend when they pass from one medium to another?

6 Describe dispersion in your own words.

7 Which properties of a light wave change and which remain the same when undergoing refraction?

Analyse

8 The speed of light in a particular transparent plastic is $2.00 \times 10^8 \text{ m s}^{-1}$. Calculate the refractive index of the plastic. Use speed of light in a vacuum as $3.00 \times 10^8 \text{ m s}^{-1}$.

9 A jeweller is checking the brilliance (refracting power) of a diamond by passing white light through water into the diamond, while it is submerged. Determine the refractive index of the diamond, if an incident angle of 30.0° produces an angle of refraction of 16°. Use $n_{water} = 1.33$.

10 Light travels from water ($n = 1.33$) into glass ($n = 1.60$). The incident angle is 44°. Calculate the angle of refraction.

11 Calculate the critical angle for light travelling from diamond ($n = 2.42$) into air ($n = 1.00$).

12 A concave lens of focal length 15 cm is held 30.0 cm above a page of writing. Apply graphical ray tracing to find the image. Describe the image.

13 Two convex lenses are exactly the same size and shape but lens A is made of a glass with a higher refractive index than lens B.

a Identify the lens with the longer focal length.

b Identify the lens that would provide the largest magnification.

11.5 Interference and diffraction of light

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- explain that a wave model of light can describe diffraction
- explain that a wave model of light can describe interference
- describe Young's double slit experiment as evidence of the wave nature of light
- describe the qualitative effect of wavelength, distance from the screen and slit separation on interference patterns.

Scientists continued to explore the nature of light throughout the 19th century. Two key observations provided crucial evidence supporting the wave nature of light, independent of measurement of the speed of light. The observations involved the diffraction and interference of light.

DIFFRACTION

If you have ever watched water waves lap against a partial barrier—such as a rocky outcrop or sand bar at the beach—you may have noticed their ability to bend around and enter the region behind the barrier. An example of this is shown in Figure 11.5.1. This phenomenon is known as diffraction. As it is an observed property of both water waves and other waves, such as sound waves, it contributed to the acceptance of the wave nature of light.

FIGURE 11.5.1 Water waves will bend around an obstacle.

It is an observed property of waves that when obstacles are placed in their path the waves will bend around and enter the area behind the barrier. This also applies when waves pass through an aperture, which can be thought of as a pair of barriers, as shown in Figure 11.5.2. In Figure 11.5.2a, the waves have bent into a large region behind the barrier in the ripple tank. In Figure 11.5.2b, a wider opening or gap is used and the waves have not bent around as far behind the edge of each barrier. From the diffraction of waves in Module 9.5, the following relationship has been observed:

- Wavelengths much smaller than the diameter of the gap or obstacle produce a small degree of bending around the edges.
- Wavelengths comparable to or larger than the diameter of the obstacle or gap produce significant bending or diffraction.

The relationship can be expressed as the ratio:

$$\frac{\lambda}{w}$$

which determines the amount of diffraction where λ is the wavelength (m) w is the width of the obstacle or gap.

Diffraction almost always occurs when waves travel through gaps. In fact, diffraction occurs even if the $\frac{\lambda}{w}$ ratio goes as low as $\frac{1}{100}$. The higher the ratio, the more the diffraction. The lower the ratio, the less the diffraction.

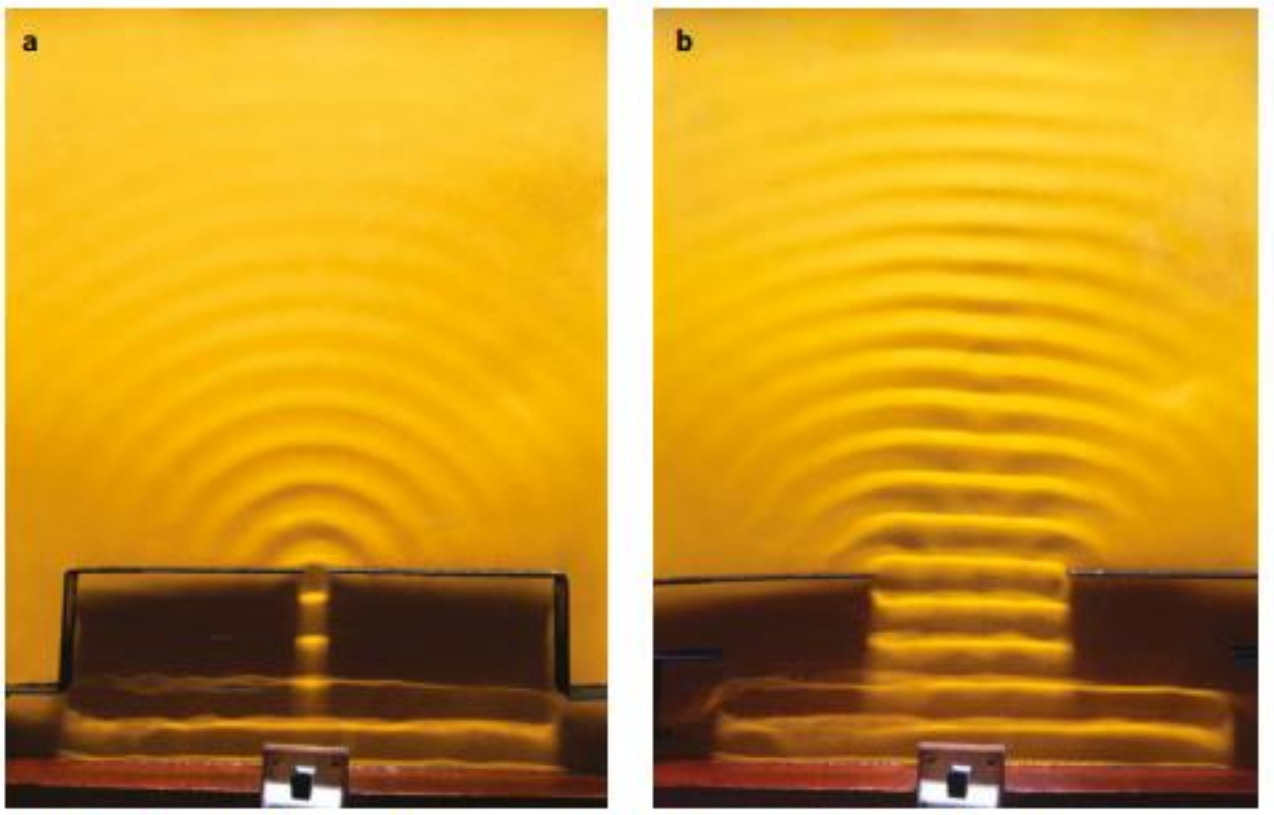


FIGURE 11.5.2 The diffraction of water waves in a ripple tank (a) Significant diffraction occurs when the wavelength approximates the slit width, $\lambda = w$. (b) As the gap increases, diffraction becomes less obvious, because $\lambda < w$.

Diffraction effects caused by light are not as readily observed in everyday circumstances. The patterns around the shadows of objects caused by the diffraction of light require particular conditions to be seen clearly.

Practical observations of diffraction of light

You can observe a crude single-slit diffraction pattern by making a 3 cm cut perpendicular to the edge of a small piece of dark (opaque) paper. Hold the paper about 5 cm in front of one eye and look through the slit at a light source such as a computer screen. You should see stripes or bands of light and dark. These patterns are often called **fringes**. Pull the paper so that the slit widens and observe the effect on the diffraction pattern.

An object or aperture is best illuminated by a point source of light, so the diffraction fringes created by each part of a large light source do not overlap and uniformly illuminate the area adjacent to the shadow. Similarly, monochromatic (a single wavelength) light works best. If white light is used, fewer or no fringes may be seen, as the different wavelengths in the white light produce fringes of different spacing and these too may overlap.

Note that the wavelengths of visible light are 400–700 nm, much smaller than anyone originally imagined. Accordingly, the wavelength of visible light is far smaller than the size of any everyday object, so diffraction is not readily seen. Consequently, beams of light are observed to travel in straight lines and cast sharp shadows. This is why the behaviour of light is, in most circumstances, modelled successfully by the ray diagrams described in the earlier sections of this chapter.

To produce an observable example of single-slit diffraction, a single aperture can be used, as shown in Figure 11.5.3. The observed diffraction pattern is a series of bright and dark fringes produced on the screen, which can be modelled by waves that are said to interfere constructively and destructively. The extent of the diffraction of the light waves depends on the relative sizes of the wavelength, λ, and the diameter or width of the gap, w (as it does for water waves). It is useful to consider the amount of diffraction by referring to the ratio of wavelength to gap width $\frac{\lambda}{w}$.

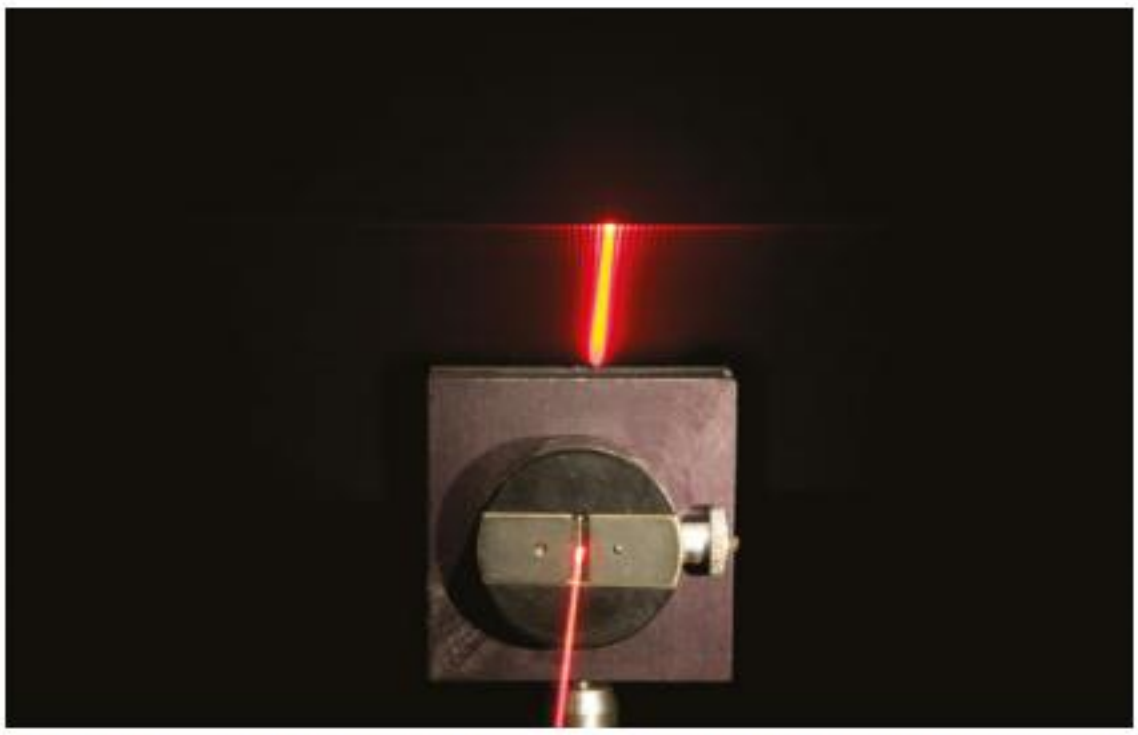


FIGURE 11.5.3 The extent of the diffraction pattern changes as the width of the slit changes. If the slit size decreases, the pattern produced will widen.

This ratio determines the spacing of the individual fringes and the width of the overall diffraction pattern. The diffraction pattern will have a central fringe that is twice as wide as the other fringes.

- If the wavelength is constant and the aperture or gap is made smaller, then greater diffraction is seen.
- If different wavelengths enter the same gap, then those with a small wavelength will undergo less diffraction than those with longer wavelengths.

That means there will be greater diffraction of red light than blue light, as shown in Figure 11.5.4.

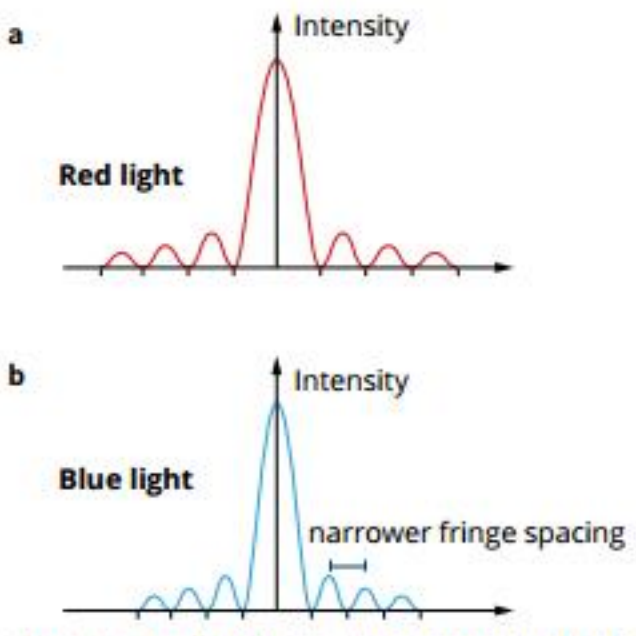


FIGURE 11.5.4 Small apertures are required in order to demonstrate the diffraction of light so (a) red light is diffracted to a greater extent than (b) blue light. Red light has a longer wavelength, which results in more widely spaced fringes and a wider overall pattern.

Diffraction gratings

A diffraction grating is a flat piece of glass or plastic with as many as 10000 lines per centimetre etched on it. Each line is a scratch that is opaque to light that is incident on the surface. The gaps between the scratches remain transparent. If white light is shone onto the surface, each wavelength produces a set of fringes at different angles to the incident beam. The result is the light will be separated into its component colours, and multiple-coloured spectra are produced, as shown in Figure 11.5.5. You may have observed this effect on the bottom of an old CD or DVD, if you still have any of these. In the science laboratory, diffraction gratings can be used to determine the wavelength of particular light by measuring the distance between fringes of the same colour.

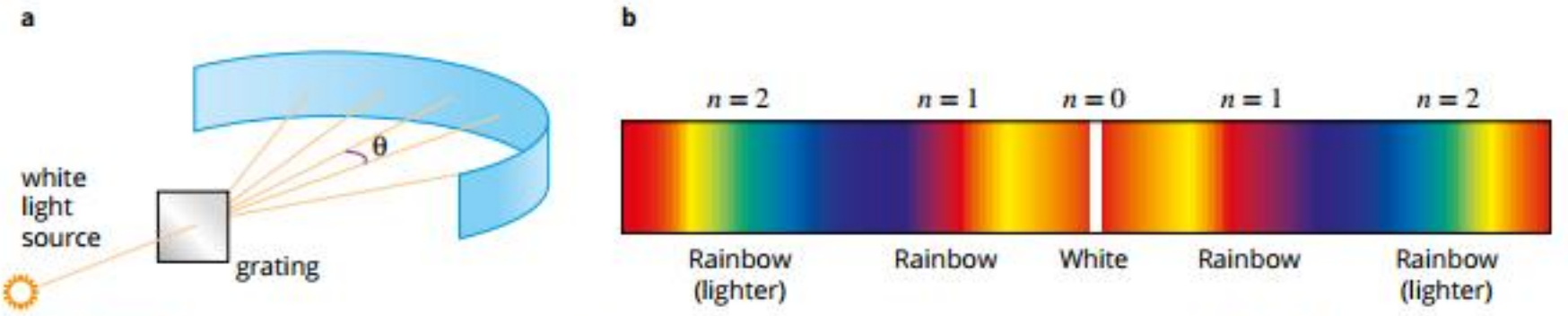


FIGURE 11.5.5 (a) The interference pattern from a diffraction grating for white light extends through large angles. (b) The maxima are so sharp that the component wavelengths of white light will separate into a spectrum on the screen.

INTERFERENCE OF LIGHT

In 1801, an English physician and physicist, Thomas Young, investigated the wave nature of light. In his experiment, Young projected a narrow beam of light through a pair of closely spaced slits in a darkened room. The light from the slits was viewed on a screen some distance away. Young saw a series of alternating bright and dark fringes on the screen, as shown in Figure 11.5.6. The centre of the distribution pattern corresponds to the centre of the brightest central fringe, known as the central maximum.

Young knew about the interference of water and sound waves, so he could only conclude that light too must have a wave nature. Young suggested that at each bright band, the light coming from each source was added, and that at each dark band it was being cancelled.

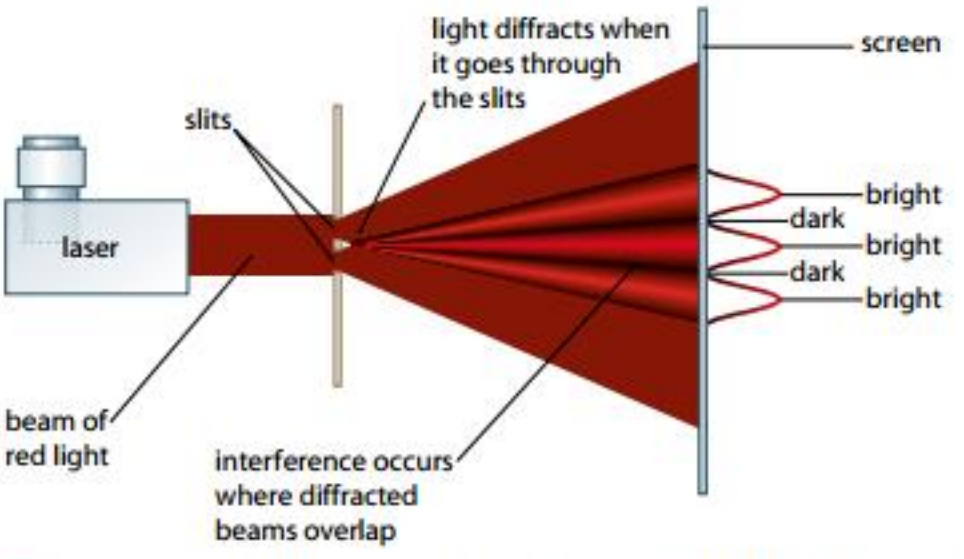


FIGURE 11.5.6 In a reproduction of Young's experimental set-up, the bright and dark fringe pattern that is observed on the screen supports a wave model for light.

To see how this is possible, consider this modern version of Young's experiment. Monochromatic light (light consisting of only one wavelength) is directed at two narrow, parallel slits, S_1 and S_2, which are placed very close together. A screen is positioned at some distance behind the slits. As the light passes through each slit, it diffracts, and two sets of circular wavefronts emerge and spread into the region beyond the slits, as shown in Figure 11.5.7a.

The incident light consists of plane waves that come from the same source, so the light emerging from each slit will be **in phase**. This means that if there is a crest emerging from S_1, there will also be a crest emerging from S_2.

At every point on the screen, a wave train from one slit will meet a wave train from the other slit. The resulting intensity at each point is determined by the principle of superposition, in which constructive interference and destructive interference of waves produce antinodes where the waves add to form a bright line and nodes where the waves cancel each other out to form a dark line. Figure 11.5.7b is an example of an **interference pattern**.

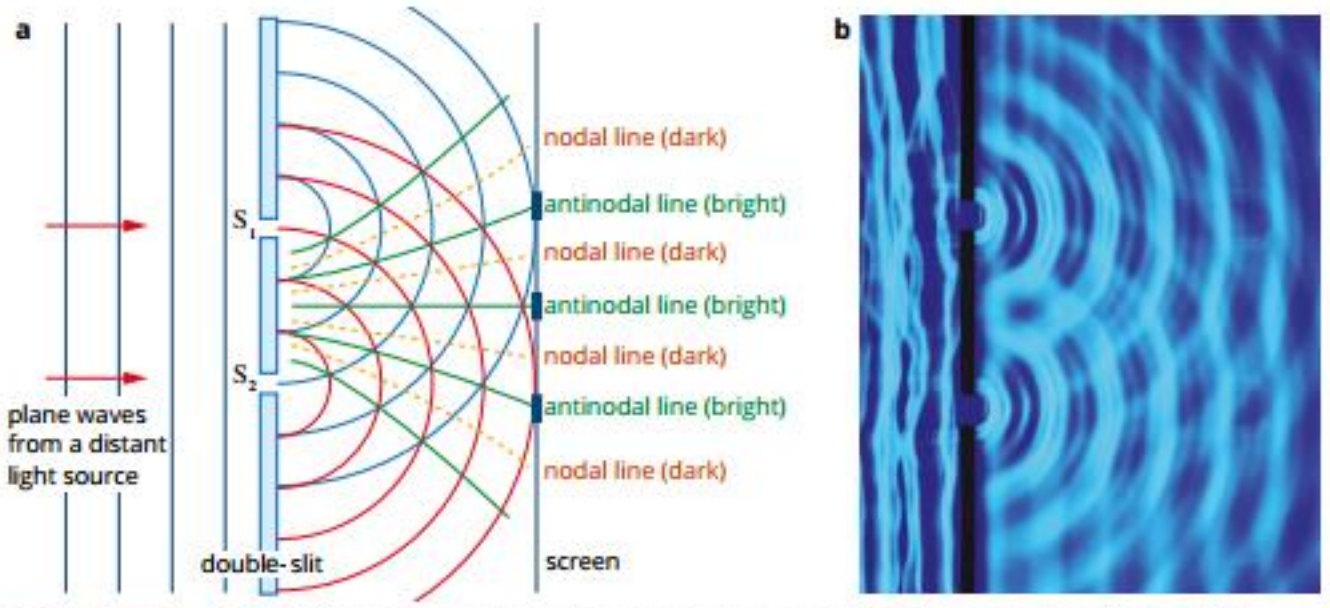


FIGURE 11.5.7 (a) Light from a monochromatic and distant source is incident on a pair of slits. Plane waves enter each slit at the same time, resulting in two sets of circular waves that overlap and spread into the region beyond the slits. The circular waves then interfere to produce a series of nodal (dark) lines and antinodal (bright) lines. (b) This interference pattern of alternating nodal and antinodal lines can also be seen in water waves when a pair of dippers oscillate in phase in a ripple tank.

FACTORS AFFECTING INTERFERENCE PATTERNS

Factors that affect the fringe spacing, which is the distance between adjacent bright bands on the screen (Figure 11.5.8), include the wavelength of light, the separation between the two slits and the distance to the screen. If the viewing screen is moved further from the two slits, the fringes will appear further apart. Alternatively, using light of a longer wavelength will also result in increased fringe spacing. However, if the screen position and wavelength of light are held constant, the fringe spacing can also be increased by reducing the separation of the slits.

When observing interference patterns created by two slits, the fringe spacing can be increased by:

- **increasing the wavelength**
- **increasing the distance to the screen**
- **decreasing the distance between the slits.**

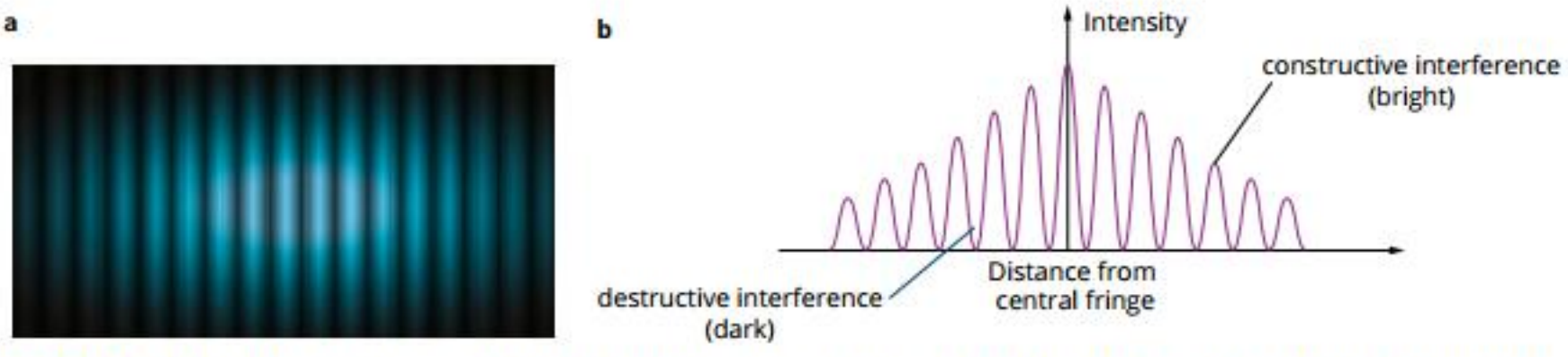


FIGURE 11.5.8 (a) The fringes produced by double-slit interference are evenly spaced. The central band is brightest and the adjacent fringes diminish in intensity. (b) The double-slit interference pattern can be considered in terms of an intensity distribution graph. The horizontal axis represents a line drawn across the screen.

Different colours (wavelengths) of light produce different fringe spacing. Young was the first to determine approximate values for the various wavelengths of visible light by using his understanding of the interference of light from two sources. He showed that the physical property distinguishing the different colours of light from each other is their wavelength, a key property of a wave model of light.

11.5 Review

SUMMARY

- A wave model of light can explain interference.
- Waves diffract (bend) as they pass by an obstacle or through a gap. The extent of the diffraction is determined by the relative sizes of the wavelength, λ, and the obstacle or gap diameter, w.
- The interference pattern seen in a double-slit experiment consists of alternating bright and dark fringes resulting from constructive and destructive interference of monochromatic (single frequency) light. The small wavelength for light (400–700 nm) requires that the slits are very close to each other and the screen is a significant distance from the slits.
- The fringe spacing of an interference pattern can be increased by using light of a longer wavelength (lower frequency), placing the viewing screen or film further from the pair of slits, or by decreasing the separation of the slits.

KEY QUESTIONS

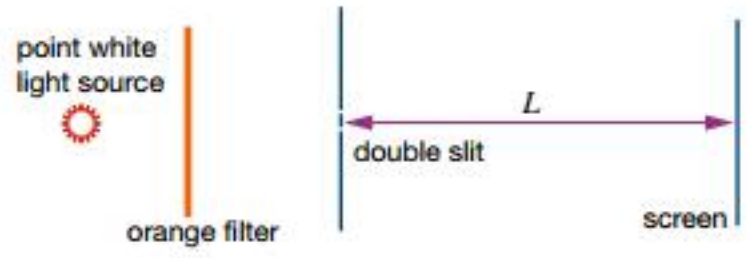
Describe

1 When light is shone on the playing surface of a DVD or BluRay disc, rainbow patterns can be observed on the playing surface. State the key wave behaviour of light that leads to these rainbow patterns.

2 Young's experiment can be modelled using circular waves in a ripple tank. Describe the observation(s) of the waves that would be representative of constructive interference.

The following information applies to questions 3–5.

A double-slit interference experiment is set up to produce an interference pattern on a screen at a distance L from the slits. The arrangement is illustrated in the diagram below.



3 List the ways in which increased fringe spacing could be produced on the screen.

4 If the orange filter is removed and white light passes through the slits, coloured fringes are observed. State the phenomenon that is responsible for this observation. Justify your explanation.

5 Compare the results seen on the screen of a diffraction experiment and interference experiment for light.

Apply

6 Explain how changing the gap width or wavelength of light would affect the amount of diffraction observed.

7 Two students are trying to replicate Young's double-slit experiment. One uses torch light and the other uses light from a laser. Identify which student is more likely to obtain the expected diffraction pattern. Explain the reasoning behind your choice.

Analyse

8 Yellow light is directed through a single thin gap. It has a wavelength of 580 nm. Will a gap width of 500 nm produce any diffraction?

11.6 Intensity

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the concept of intensity of light and its proportionality to the square of amplitude
- use the relationship $I \propto \frac{1}{r^2}$ to solve problems involving the intensity of light at a distance from the source.

In mathematics, a ray continues infinitely in one direction. In the real world, a light ray does not continue indefinitely due to the wave nature of light; it reduces in intensity due to its wave behaviour, the further it gets from its source. In physics, **intensity** is a measure of the rate at which energy passes through an area of space. This corresponds roughly to the 'brightness' of the light.

INTENSITY AND DISTANCE

In general, the intensity of the light, I, at a distance r from the source is inversely proportional to the square of the distance from the light source.

The unit of intensity is watts per square metre, $W\,m^{-2}$. Note that the human eye is more sensitive to some colours than to others. For example, eyes are most sensitive to greenish-yellow light. There are also types of light in the light spectrum, such as infrared or ultraviolet light, that eyes cannot see at all.

When discussing how people perceive the brightness of a light source, a standard measure in $W\,m^{-2}$ is used. This accounts for the color sensitivity of an individual's eyes.

As light wavefronts radiate outwards from a point source as a sphere, as shown in Figure 11.6.1, the initial energy is spread over an increasingly larger area. Recall that the surface area of a sphere is $4\pi r^2$, where the 4 and the π are constants. So, the surface area will increase with the square of the radius.

Assume that light energy flowing through the shaded box at a distance, r, represents an intensity, I, of the light source.

- For r, the light energy flowing through an area is proportional to r^2.
- For $2r$, the light energy flowing through an area is proportional to $(2r)^2$, which is 4 times as large as at r. This means that the light at this point will be only one-quarter as bright as at r:

$$I_2 = \frac{1}{4} I_1$$

- For $3r$, the light energy flowing through an area is proportional to $(3r)^2$, which is 9 times as large as at r. This means that the light at this point will be only one-ninth as bright as at r:

$$I_3 = \frac{1}{9} I_1$$

The relationship between the intensity of light at any two points at different distances, r_1 and r_2, from a light source can be found by:

$$I_1 r_1^2 = I_2 r_2^2$$

That the intensity of light decreases with the square of the distance from the source provides further evidence of the wave nature of light and is referred to as an **inverse square law**.

In physics, there are a number of phenomena that decrease in strength or intensity as the square of distance increases. The intensity of sound waves varies according to an inverse-square relationship. Gravitational, electrostatic and magnetic effects all follow this same type of relationship, as will be seen in later studies.

$I \propto \frac{1}{r^2}$

where

I is the intensity of the light source ($W\,m^{-2}$)

r is the distance from the light source (m).

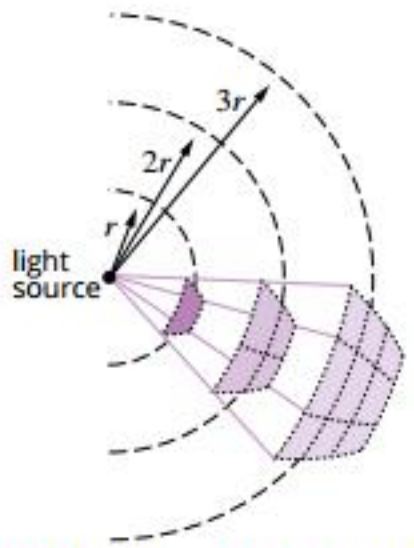


FIGURE 11.6.1 As light moves away from the source, it spreads out radially. As the radius increases, the same amount of energy passes through a larger area. The area increases with the square of the radius, so the intensity decreases by this same ratio.

$I_1 r_1^2 = I_2 r_2^2$

where

I_1 and I_2 are the intensities at points 1 and 2 respectively ($W\,m^{-2}$)

r_1 and r_2 are the distances of points 1 and 2 respectively from the light source (m).

Worked example 11.6.1

CALCULATING INTENSITY

The light from a 25 W compact fluorescent light bulb has an intensity of 11 W m^{-2} at a distance of 1.0 m from the bulb. Calculate the intensity of the light at a distance of 2.0 m from the bulb.	
Thinking	**Working**
Recall the formula for intensity.	$I_1 r_1^2 = I_2 r_2^2$
Rearrange the formula to make I_2 the subject.	$I_2 = \frac{I_1 r_1^2}{r_2^2}$
Substitute the appropriate values into the formula and solve.	$= \frac{11 \times 1^2}{2^2}$ $= 2.8\ \text{W m}^{-2}$

➤ Try yourself 11.6.1

CALCULATING INTENSITY

The intensity of the light 50.0 cm away from a light-emitting diode (LED) is 0.016 W m^{-2}. Calculate the intensity of the light at a distance of 10.0 cm from the LED.

SKILLBUILDER

Using proportional reasoning in physics

If the type of relationship between two variables is known (for example, direct, quadratic, inverse, inverse-square), you can use your knowledge of proportion to determine how much one variable will change due to a change in the other variable.

Consider a situation where there is a direct relationship between two variables x and y ($x \propto y$). If you are told that the value of x will double, then you can predict that y will also double. This is an example of 'proportional reasoning'.

Similarly, if there is an inverse relationship between x and y ($x \propto \frac{1}{y}$) then you know if the value of x is doubled, the value of y will be halved.

There are many different strategies that can be used to solve problems involving proportional reasoning. One reliable method is outlined below.

1. Describe the relationship between variables as a statement of proportion (e.g. $x \propto \frac{1}{y}$).
2. Rewrite the proportionality as an equation by introducing a constant of proportionality (e.g. $x = k \times \frac{1}{y} = \frac{k}{y}$).
3. Transpose the equation to make the constant the subject (e.g. $k = xy$).
4. As the constant of proportionality will not change, describe the relationship between an original set of values for the variables (e.g. x_1 and y_1) and the changed set of values (e.g. x_2 and y_2) to write an equation ($k = x_1 y_1 = x_2 y_2$).
5. Describe the change to one variable as an equation (e.g. if x_1 is doubled, then $x_2 = 2x_1$).
6. Substitute the equation from step 5 into the equation from step 4 (e.g. $x_1 y_1 = (2x_1) y_2$).
7. Simplify this new equation to describe the change in the other variable (e.g. cancelling x_1 from both sides: $y_1 = 2y_2$, therefore $y_2 = \frac{1}{2} y_1$).
8. Interpret the answer (e.g. y has been halved).

Note: This process is made much simpler when physical relationships are expressed in a way that means that the initial steps 1–4 have already been completed (e.g. $I_1 r_1^2 = I_2 r_2^2$).

Worked example 11.6.2

CALCULATING INTENSITY CHANGES USING PROPORTIONAL REASONING

The distance between a compact fluorescent light bulb and the observer is doubled. Determine by what ratio the intensity of the light from the bulb will change.	
Thinking	**Working**
Recall the formula for intensity.	$I_1 r_1^2 = I_2 r_2^2$
Describe the change to the radius as an equation.	$r_2 = 2r_1$
Substitute this relationship into the formula for intensity.	$I_1 r_1^2 = I_2 r(2r_1)^2$
Simplify this equation to describe the change in intensity.	$I_1 r_1^2 = I_2 \times 4r_1^2$ $\therefore I_1 = I_2 \times 4$ $\therefore I_2 = \frac{1}{4} I_1$
Interpret the answer.	The intensity has reduced by a quarter.

➤ Try yourself 11.6.2

CALCULATING INTENSITY CHANGES USING PROPORTIONAL REASONING

A light-emitting diode (LED) is brought five times closer to a light meter. Determine by what ratio the measured intensity of the LED will change.

The inverse square law for intensity of a light source at a distance, r, from an observer can be applied to light sources as close as a light in the same room and as distant as a star or galaxy, as long as the medium in between is constant (Figure 11.6.2). Where light is dispersed, reflected or absorbed by changes in the medium, then these other factors mean that the intensity may be greater or less than expected.

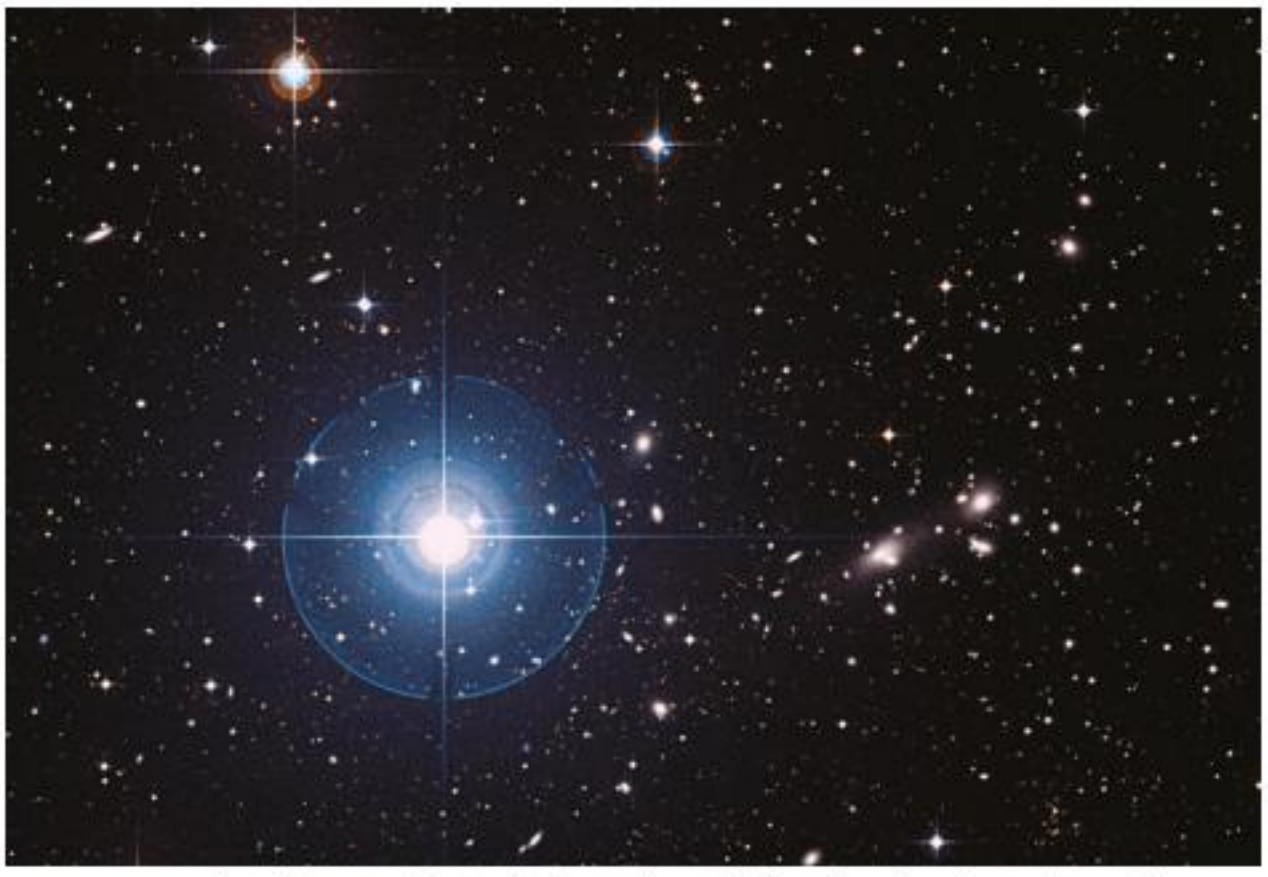


FIGURE 11.6.2 The distance to distant galaxies, such as the Klemola galaxy cluster pictured here, or the relative intensity can be calculated using the relationship between intensity and distance from the source, provided that the medium between source and observer is constant.

INTENSITY AND AMPLITUDE

In the previous section intensity was defined as the rate at which light energy passes through an area of space. This makes intensity an energy per unit of time quantity. The amplitude of a light wave, however, is directly related to the brightness of the light. A higher amplitude light wave is a brighter light. A lower amplitude light wave is a dimmer light.

Intensity and amplitude in light waves are directly related: the greater the energy, the larger the amplitude of the wave, and vice versa. Specifically, the energy of a wave is proportional to the square of the amplitude, A. Therefore, intensity, I, is proportional to A^2.

- If the amplitude of a light wave is doubled, the intensity will change by two squared or 2^2 or by a factor of 4.
- If the amplitude of a light wave is tripled, the intensity will change by three squared or 3^2 or by a factor of 9.
- Likewise, if the amplitude of a light wave is halved, the intensity will change by half squared or $\left(\frac{1}{2}\right)^2$ or by a factor of $\frac{1}{4}$.

Unlike the inverse square law that connects intensity and distance, where the intensity decreases as the square of the distance increases, the rule connecting intensity and amplitude states that as the square of the amplitude increases, the intensity increases. This is a direct square rule, rather than an inverse square rule.

This relationship between intensity and amplitude applies to all waves, not just to light, which is further evidence of the wave nature of light.

i The relationship between intensity and amplitude can be written as:

$I \propto A^2$

where

I is the intensity of the light source ($W\,m^{-2}$)

A is the amplitude of the light source.

11.6 Review

SUMMARY

- Intensity is a measure of brightness or the rate at which light energy passes through an area of space. The unit for intensity is Wm^{-2}.
- The relationship between the intensity of light at two points at different distances from a light source is given by $I_1 r_1^2 = I_2 r_2^2$.
- The reduction in intensity with the square of the distance from the source provides further evidence of the wave nature of light.
- Proportional reasoning can be used to simplify calculations where there is a standard relationship between two variables.
- The inverse square law for the intensity of light from a source at a distance r, only applies when the medium between source and observer is constant.
- Intensity is proportional to the square of amplitude. This relationship can be written as $I \propto A^2$.

KEY QUESTIONS

Describe

1 How is the energy of a wave related to its amplitude?

2 What visible characteristic of light is the amplitude of a light wave related to?

Apply

3 The change in intensity, I, of a light source with distance is further confirmation of the wave nature of light. Explain why this is the case.

Analyse

4 A light source is 5.0 m from an observer. Calculate the intensity relative to the intensity at the source.

5 Two observers, A and B, are 1.0 m and 3.0 m respectively away from a point light source. Calculate the relative intensity of the light source seen by observer A compared with that seen by observer B.

6 The distance between a light source and an observer is increased by a factor of 2.5. Calculate the factor by which the intensity of the light will increase or reduce.

7 The amplitude of a light wave reduces by $\frac{1}{4}$. What effect does this have on the intensity of the light?

8 The intensity of a light wave goes up by a factor of 4. By what factor does the amplitude change?

11.7 Polarisation

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe polarisation using a transverse wave model of light
- explain plane polarisation of light using a transverse wave model of light
- describe applications of polarisation.

Further evidence for the wave nature of light is the finding that light can be polarised. Most light sources, including the Sun, produce unpolarised light.

- In Figure 11.7.1a, the orientation of the light waves are not aligned. This is **unpolarised light**.
- In Figure 11.7.1b, the orientation of the light waves are aligned. This is **polarised light**.

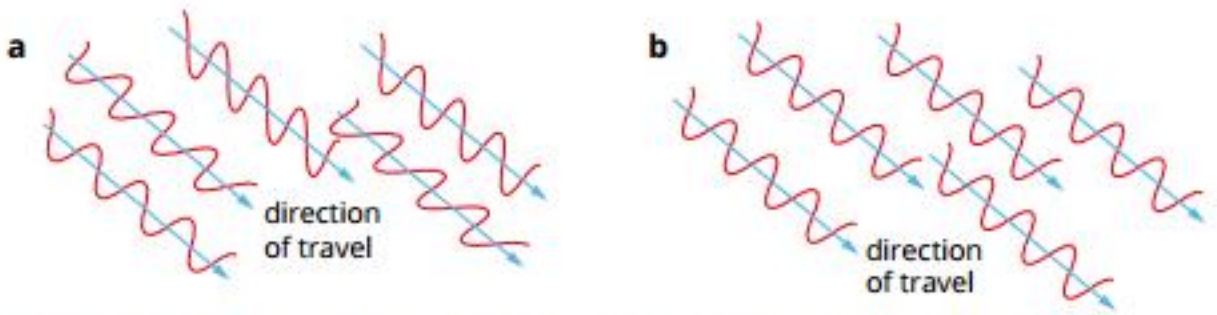


FIGURE 11.7.1 (a) Unpolarised light, such as that emitted by the Sun or a light globe, has transverse waves that are not in alignment with one another. (b) Polarised light waves, such as those from a laser, have transverse waves that vary in the same plane as one another.

A polariser demonstration set is shown in Figure 11.7.2. The fact that unpolarised light can be converted into polarised light provides strong evidence that light is a wave. Also, the fact that light can be polarised indicates that it is a transverse wave because longitudinal waves cannot be polarised.

FIGURE 11.7.2 A polariser demonstration set usually consists of a pair of thin treated plastic discs or sheets that allow investigation of polarised and unpolarised light.

POLARISING UNPOLARISED LIGHT

The best-known way to convert unpolarised (non-aligned) light to polarised (aligned) light is by using **polarising filters**. These filters have molecules that block all wave components except those in the plane that is aligned in a particular direction. Figure 11.7.3 on page 460 demonstrates this process using a 'slit' to represent the filter. Keep in mind that filters are solid materials, usually specially treated plastics.

- If a light wave is aligned with the filter, then it will pass straight through the filter and maintain its original amplitude. All the light energy aligned in this way will pass through. A vertically orientated filter will only allow light that is vertically orientated to pass through, as shown in Figure 11.7.3a.
- If a light wave is completely out of alignment with the filter, then it will be blocked. The filter will absorb the light, as shown in Figure 11.7.3b.
- If a light wave has only a component of its wave in alignment with the filter, then only this component of the wave will be transmitted. The emerging wave will have a significantly reduced amplitude. A portion of the light energy will not pass through the filter, as shown in Figure 11.7.3c. The emerging light is described as 'vertically polarised'.

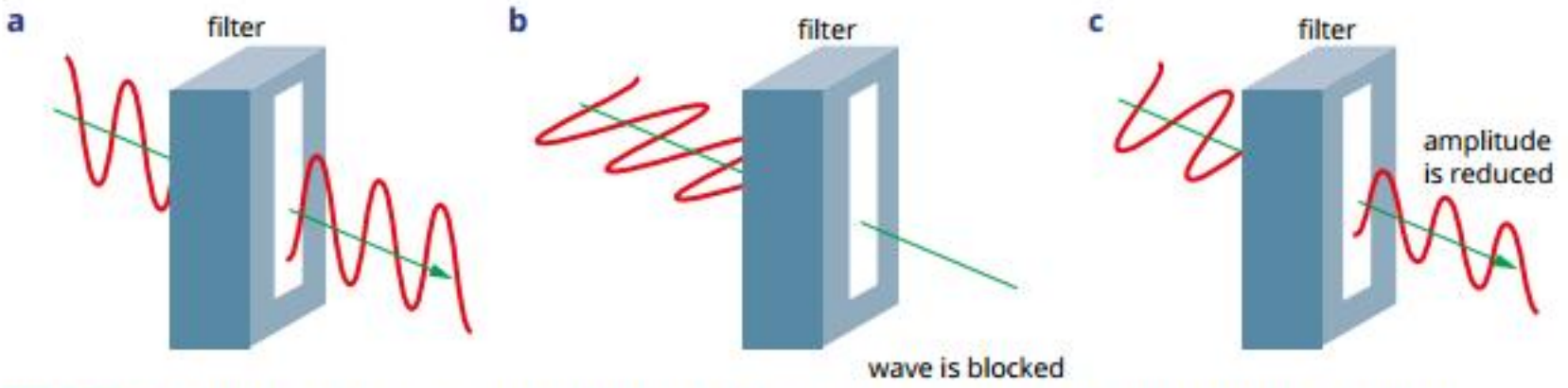


FIGURE 11.7.3 (a) The first filter allows vertically polarised light to pass through, matching the orientation of the slits. (b) All horizontally polarised light is blocked. (c) The horizontal component of the light is suppressed matching the slit width, resulting in vertically polarised light of reduced amplitude. The emerging light will be less bright than the incident light.

If unpolarised light is incident on the filter (at 90°), then only vertically polarised light would emerge. A pair of polarising filters with a very fine slit width placed at right angles would prevent all light from passing through. One filter would block all the horizontal components and the other filter would block the vertical components, as shown with the polarising sunglasses in Figure 11.7.4. In practice, the physical width of the polarising 'slit', while very small, will allow small amounts of very short wavelengths through. This light will be in the violet end of the spectrum. As a result, typically, when looking through a pair of crossed polaroids, low intensity violet light can be seen.

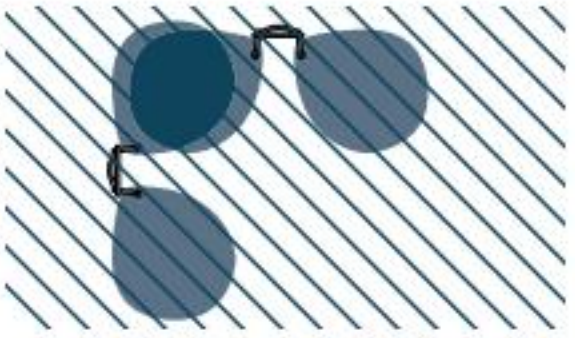


FIGURE 11.7.4 Polarising materials crossing over at right angles to one another will prevent any light from passing through.

PLANE POLARISATION OF REFLECTED LIGHT

When outdoors on a bright, sunny day, the smooth, highly reflective, horizontal surfaces around you are a significant contributor to the amount of light entering your eyes. Think of the glare from the surface of the ocean—or a snowy mountain—on a sunny day.

Fortunately, light that is reflected from smooth, horizontal surfaces tends to be polarised (aligned) in a horizontal direction. This is termed the **plane polarisation** of reflected light. An appropriately orientated polarising filter can be used. Lenses in a pair of polarised sunglasses are polarising filters orientated to block the horizontal wave components of reflected light, allowing only the vertical components through. Therefore, the intensity of light, or glare, is markedly reduced.

OTHER APPLICATIONS OF POLARISATION

If you have ever used polarised sunglasses, you may have noticed one of the other effects of polaroids, particularly when driving. The amount of glare off the windscreens of other cars is substantially reduced, but in its place can be seen what appear to be rainbows within the glass. This is particularly true of modern laminated glass windscreens that are part of the car structure and therefore come under some stress.

You can try this yourself. Place a clear piece of thick plastic, or similar, between two polaroids. Shine a light source through the polaroids then flex or twist the piece of plastic and note any changes in the appearance of the plastic. Initially, the plastic will look quite flat. If the polaroids are twisted at right angles to each other, the plastic may be seen as a lighter area, suggesting that the plane of the light that travelled through the first polaroid is being partially rotated by the passage through the plastic. When the plastic is twisted, rainbows appear across the surface of the plastic. The more stress that is applied, the tighter the pattern of the rainbows. The patterns are indicating where the stress in the plastic is greatest and hence where it is most likely to break.

This application of polarisation is referred to as photoelasticity and was originally explained by Scottish physicist David Brewster, before its widespread use in the early part of the 20th century. This method determines stress distribution in a material experimentally and gives a fairly accurate picture of stress distribution around likely breaking points in materials. With the advent of computer monitoring, the method became less common, but it is still used for determining stress concentration in irregular geometries or where mathematical models are too cumbersome or slow to develop. The digital 'polariscope' using LEDs allows continuous monitoring of structures under loads, contributing to the study of causes of fracturing of materials, as shown in Figure 11.7.5.

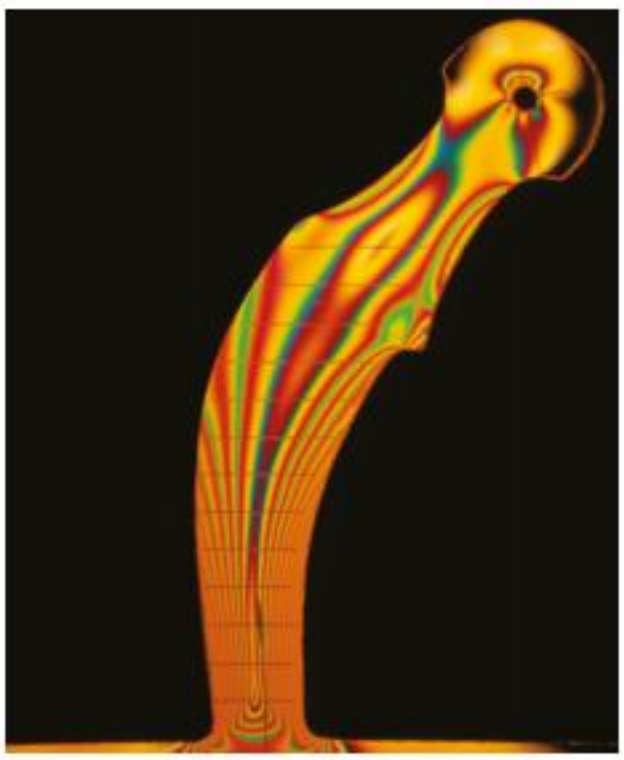


FIGURE 11.7.5 Stress patterns in a plastic model of a proposed human hip joint replacement. The model has been photographed between two polaroids. Points of discontinuity in the patterns indicate where the model is likely to break and changes can be made to the implant before being produced out of the final metal material.

Similar patterns can be observed in some solutions, termed chiral solutions. Since 1812, it has been known that certain molecules are optically active and can rotate plane-polarised light. For example, table sugar is an optically active substance. Table sugar has a tetrahedral carbon atom that has four different groups attached to it. This carbon is known as a chiral centre. The geometry of the chiral centre allows the formation of mirror image molecular forms under the right conditions. One of the molecular forms can rotate plane-polarised light to the right and the other mirror image molecular form is able to rotate this light to the left by the same angle.

Experimentation is the only way to determine which form of molecule is which. The procedure consists of preparing a solution of known concentration and placing it between two polarising filters. A polarimeter, essentially two polaroids with a scale to measure the difference in angle of polarisation between them, measures the amount and direction of rotation of the plane-polarised light (Figure 11.7.6). The specific angle is a fundamental property of the chiral solution, and polarimetry makes it possible to determine the purity of solutions of known compounds and identify unknown substances from a short list.

FIGURE 11.7.6 A sample bottle of sugar solutions placed between two polaroids will rotate the polarised light from the first polaroid by an amount that is a property of the type of solution, the concentration and temperature. The second polaroid can be used to determine the amount of rotation.

11.7 Review

SUMMARY

- Unpolarised light waves are not in alignment with one another. Polarised light waves are aligned in the same plane as one another.
- Polarising filters can convert unpolarised light into polarised light, providing strong evidence that light is a transverse wave.
- Light reflected off a horizontal surface is said to be partially plane polarised.
- Polarisation can be used to determine the likely stress and breaking points in manufactured equipment during design. This application is referred to as photoelasticity.
- A polarimeter can be used to determine the concentration, substance and temperature of optically active solutions, termed chiral solutions. Sugar solutions are an example of a chiral solution.

KEY QUESTIONS

Describe

1 Describe the effect that a polarising filter has on unpolarised light.

2 Light reflecting off a horizontal surface is said to be plane polarised. Describe the term 'plane polarised'.

3 In some instances, dim violet light can still be seen after light has travelled through two polaroids at right angles to each other. Explain why this can occur.

Apply

4 State the factor by which the intensity of the unpolarised light will be reduced.

5 A second polaroid is rotated at an angle of 90° to the first. State the percentage by which the intensity of light would be reduced if the light travels through the single polaroid first.

6 A second polaroid is rotated at an angle of 180° to the first. Describe the factor by which the intensity of light would be reduced if the light travels through the single polaroid first.

7 Explain how polarisation supports a wave model of light.

Analyse

8 A polarising filter is positioned so that it produces vertically polarised light. If another filter is orientated at an angle of 30° to this filter, describe what happens to the intensity of the light.

Chapter review

11

KEY TERMS

absolute refractive index
centre of curvature
collinear
concave
convex
corpuscular
critical angle
dispersion
electromagnetic radiation
electromagnetic spectrum
focal length
geometrical optics
in phase
intensity (of a wave)
interference pattern
inverse square law
lens
magnification
optical density
plane polarisation
polarised light
polarising filters
principal axis
principal focus
radius of curvature
ray tracing
real image
rectilinear propagation
refraction
relative refractive index
Snell's law
spectrum
spherical aberration
spherical mirror
total internal reflection
unpolarised light
virtual image
visible light

KEY QUESTIONS

Describe

1 As light travels from quartz (n = 1.46) to water (n = 1.33) it will:
A speed up
B slow down
C stay the same speed
D be stopped all together

2 Identify which of the following statements, A–D, regarding a virtual image is correct:
A A virtual image can be projected onto a screen.
B A virtual image really exists.
C A virtual image is produced by intersecting rays.
D A virtual image is located at a point from which rays of light seem to diverge.

3 Indicate which of the following boundaries between two media will result in the greatest refraction of any light ray that crosses the boundary.
A water to air
B water to diamond
C air to diamond
D glass to air

4 State the term for the point at which parallel rays of light through a convex lens converge.

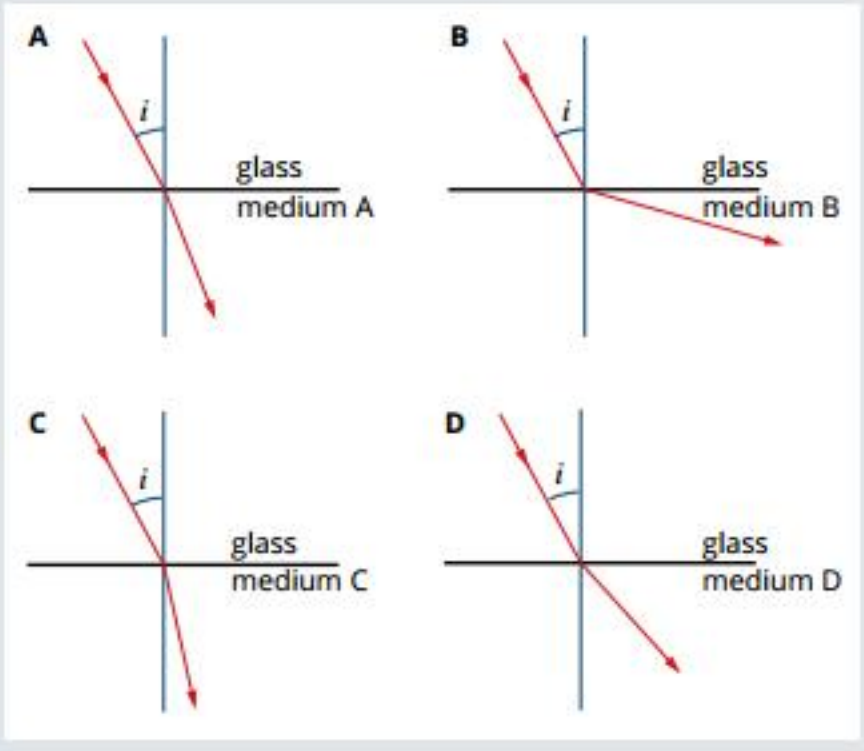
5 How does Young's double-slit experiment support the idea that light is made up of waves?

6 Describe the terms 'polarised light' and 'unpolarised light' based on the principle of light being a transverse wave.

7 Describe how the spectrum of colours reflected from a black object is different from the spectrum of light reflected by a green object.

Apply

*The following diagrams relate to questions **8–12**.*
The diagrams show light passing from glass into different media labelled A, B, C and D.



8 Determine which (one or more) media are more optically dense than glass.

9 Identify the media that have a refractive index less than the refractive index of glass.

10 Select the medium that has the highest refractive index.

11 Select the medium with a refractive index very close to the refractive index of this sample of glass.

12 Explain what happens to the speed of light as it crosses the boundary between glass and medium D.

13 If the distance between a light source and an observer is halved, determine how much the intensity of the light will change.

14 You stand 3 m in front of a plane mirror. Determine how far from you your image appears to be.

15 Explain how it is possible to see a star, even when it is actually positioned below the horizon.

16 State the physical properties of a spherical lens that determine its focal length.

17 In an experiment to investigate diffraction, the width of the gap through which light passes is reduced. State whether the amount of diffraction increases or decreases.

18 Explain why snowboarders and fishers are likely to prefer polarising sunglasses to standard darker lenses.

19 How is the wavelength and frequency of light affected when it travels from air into glass?

20 In Young's double-slit experiment, an interference pattern of bright and dark bands is produced on a screen. How would the pattern change if one of the slits was blocked off?

Analyse

21 A ray of light enters a second medium from air at an angle of incidence of 46°. If the refracted ray is deviated by 10°, calculate the refractive index of the second medium.

A 1.15
B 0.817
C 0.868
D 1.22

22 If the refractive index of water is 1.33, calculate the speed of light in water.

A $2.00 \times 10^8 \text{ m s}^{-1}$
B $2.26 \times 10^8 \text{ m s}^{-1}$
C $3.99 \times 10^8 \text{ m s}^{-1}$
D $4.33 \times 10^8 \text{ m s}^{-1}$

23 An object is placed 20.0 cm in front of a convex mirror with a radius of curvature of 30.0 cm.

a Using ray tracing, determine how far the resulting image is from the mirror.
b Describe the nature of the image.

24 A 1.0 m tall child stands 6.0 m from a concave mirror that has a radius of curvature of 4.0 m.

a Use a ray diagram to determine the height of the image and how far it is from the mirror.
b Describe the nature of the image.

25 The speed of light in air is $3.00 \times 10^8 \text{ m s}^{-1}$. As light strikes an air–Perspex boundary, the angle of incidence is 43.0° and the angle of refraction is 28.5°. Calculate the speed of light in the Perspex.

26 A narrow beam of white light enters a crown glass prism with an angle of incidence of 30.0°. In air, the white light travels at a speed of $3.00 \times 10^8 \text{ m s}^{-1}$. In the prism, the different colours of light are slowed to varying degrees. The refractive index for red light in crown glass is 1.50 and for violet light the refractive index is 1.53. Calculate the corresponding angles of refraction for red and violet light.

27 Calculate the critical angle for light passing from diamond ($n = 2.42$) into air.

28 A concave lens is held 20.0 cm above a page and the text appears to be one-quarter its original size. Use ray tracing to model the arrangement and determine:

a the nature of the image
b the distance of the image from the lens.

29 For a person sitting 75 cm away from a computer monitor, the light intensity from the monitor is 6.0 W m^{-2}. Calculate the new intensity if they moved to sit only 50 cm from the monitor.

30 A ray of light passing from air, through a layer of plate glass and back into air emerges parallel to its original direction of travel. Explain whether the ray of light has been refracted.

Interpret

31 A spinning top is decorated with all the colours of the rainbow, yet when spun it appears almost white. A second top, also with all the colours of the rainbow, appears pinkish. Explain how this could be achieved.

32 Curved mirrors are used for different purposes. Three examples are shaving and make up, shop security, and a rear-view mirror for a truck. Decide on the shape and approximate focal length suitable for each of the given applications, taking the position of the object and required features of the image into consideration.

33 Discuss the effect that the relative size of the refractive index has on the size of the corresponding critical angle.

34 Sarah accurately determines that her glasses have a focal length of +30 cm. Identify if she is myopic (short-sighted) or hyperopic (long-sighted). Justify your answer.

35 You have two pairs of sunglasses that appear identical in every respect. Assuming the brand and labelling is not available to review, describe a method by which you could determine whether the sunglasses were polarising or non-polarising without breaking the glasses.

36 What increase in amplitude of a light wave produces a 100× increase in the light intensity?

Data analysis

DATA SET 1

An experiment was conducted to investigate the relationship between the angle of incidence and the angle of refraction when white light passes from the air into a glass rectangular prism. The raw data for this experiment is shown in the first two columns of Table 1. The students conducting the experiment then calculated various ratios relating to their measurements of the angle of incidence and the angle of refraction. These ratios are shown in columns 3 to 6.

You will also need the following values:

crown glass: $n = 1.52$

flint glass: $n = 1.62$

TABLE 1 Results for white light and rectangular prism

Angle of incidence (i) (°)	Angle of refraction (r) (°)	$\frac{i}{r}$	$\frac{\cos i}{\cos r}$	$\frac{\sin i}{\sin r}$	$\frac{\tan i}{\tan r}$
10	7	1.43	0.99	1.42	1.44
15	10	1.50	0.98	1.49	1.52
20	14	1.43	0.97	1.41	1.46
25	18	1.39	0.95	1.37	1.44
30	21	1.43	0.93	1.40	1.50
35	24	1.46	0.90	1.41	1.57
40	27	1.48	0.86	1.42	1.65
45	30	1.50	0.82	1.41	1.73
50	33				
55	36	1.53	0.71	1.39	1.97
60	38	1.58	0.63	1.41	2.22
65	40	1.63	0.55	1.41	2.56
70	42	1.67	0.46	1.40	3.05

Question 1 (4 marks)

Calculate the missing values for the angle of incidence of 50°.

Question 2 (1 mark)

Which of the ratios $\frac{i}{r}$, $\frac{\cos i}{\cos r}$, $\frac{\sin i}{\sin r}$ or $\frac{\tan i}{\tan r}$ is the most constant?

Question 3 (2 marks)

The ratio $\frac{\sin i}{\sin r}$ is the refractive index, n. If the glass prism is made of either crown glass or flint glass, calculate the percentage error for each using the following formula:

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right| \times 100$$

REVIEW QUESTIONS

Topic 1: Linear motion and force

Multiple choice

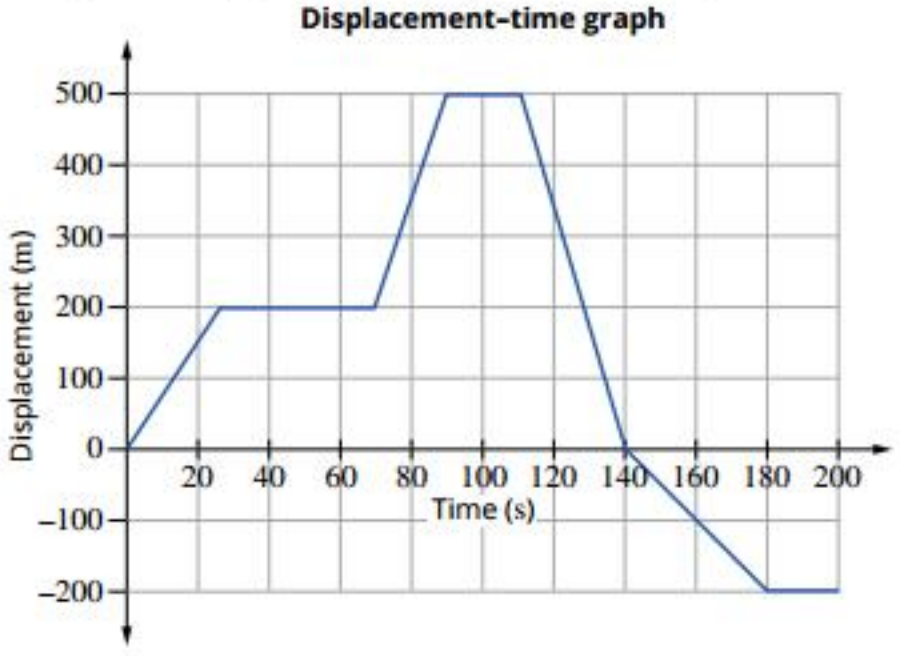
1 Select the lists below that contains only vector quantities.

A displacement, velocity, acceleration, force
B displacement, speed, acceleration, weight
C distance travelled, velocity, acceleration, force
D displacement, velocity, acceleration, mass

2 A superball hits a wall with a velocity of $7.0\,ms^{-1}$ east and rebounds with a velocity of $6.0\,ms^{-1}$ west. Determine the change in velocity of the ball.

A $1\,ms^{-1}$ west
B $13\,ms^{-1}$ east
C $13\,ms^{-1}$ west
D $1\,ms^{-1}$ east

The following information applies to Questions 3 and 4.
The graph below shows the displacement of a farmer on a motorcycle, riding north (positive) and south (negative) along a boundary of the property while counting livestock.



3 What was the total distance travelled by the farmer over the entire period?

A 500 m
B 300 m
C 700 m
D 1200 m

4 What was the total displacement of the farmer over the entire period?

A −200 m
B 0 m
C 1200 m
D −1200 m

5 A 40 kg child on a scooter is rolling down a footpath at $2.5\,ms^{-1}$. The momentum of the child is:

A $16\,kg\,ms^{-1}$ down the footpath
B $100\,kg\,ms^{-1}$ down the footpath
C $0.40\,kg\,ms^{-1}$ down the footpath
D $42.5\,kg\,ms^{-1}$ down the footpath

6 A 10 tonne truck collides with an unoccupied and stationary Mini. Select the statement that describes the situation at impact according to the third law of motion.

A The truck applies the same magnitude force on the Mini as the Mini applies on the truck.
B The truck applies a greater magnitude force on the Mini than the Mini applies on the truck.
C The truck applies a smaller magnitude force on the Mini than the Mini applies on the truck.
D The truck applies a force on the Mini but the Mini does not apply a force on the truck.

7 A 6.5 kg bowling ball is lifted from the floor to a shelf 2.2 m high. The amount of work done is:

A 43 J
B 140 J
C 4.3 J
D 14.0 J

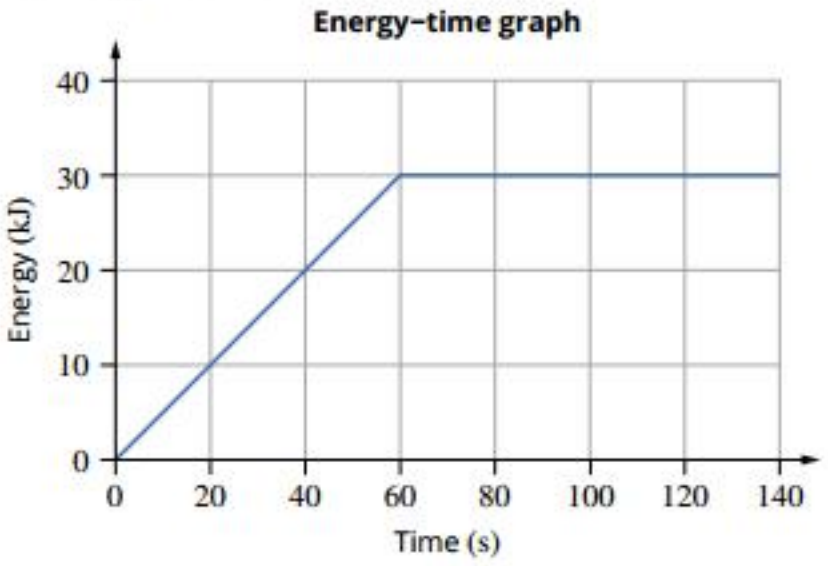
8 A gymnast is at the top of a vertical jump above the trampoline mat. Select the statement that is correct.

A She has maximal gravitational potential energy and minimal kinetic energy.
B She has maximal gravitational potential energy and maximal kinetic energy.
C She has minimal gravitational potential energy and maximal kinetic energy.
D She has minimal gravitational potential energy and minimal kinetic energy.

9 Identify the correct statement.

A In elastic and inelastic collisions, kinetic energy and momentum are not conserved.
B In elastic and inelastic collisions, kinetic energy and momentum are conserved.
C In elastic and inelastic collisions, momentum is conserved. In elastic collisions kinetic energy is conserved, but in inelastic collisions kinetic energy is not conserved.
D In elastic and inelastic collisions, momentum is conserved, but kinetic energy is not.

10 A train leaves the station, and travels on level ground. The energy of the train is shown below.



The power supplied by the engine to accelerate the train at 40 seconds is:

A 20 kJ
B 400 kW
C 20 kW
D 500 W

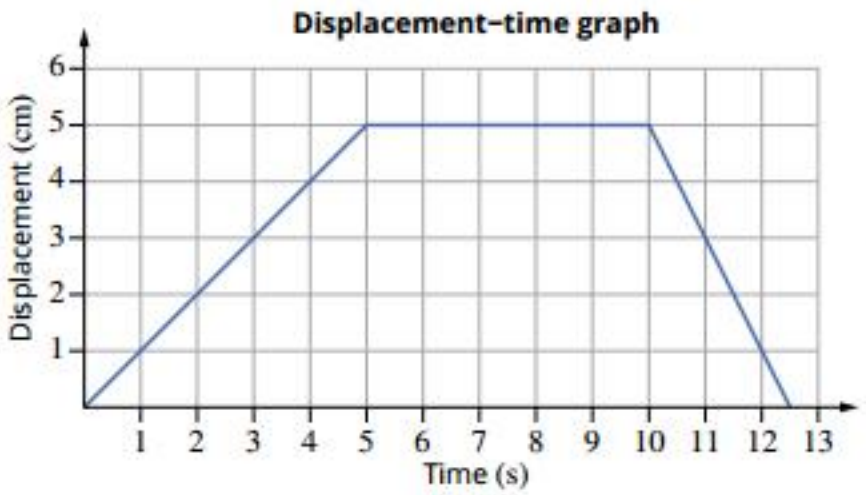
Short answer

1 A car travels 5.00 km east, 3.00 km south, 2.00 km west and 1.00 km north.

a Determine the distance, north or south, the car has travelled.

b Determine the distance, east or west, the car has travelled.

2 The graph below shows the position of an ant that is travelling in a straight line.



a Describe the following terms: displacement, average velocity and instantaneous velocity.

b Calculate the average velocity of the ant in the first 2 seconds and the instantaneous velocity at 2 seconds.

c Calculate the average velocity in the first 11 seconds, and the instantaneous velocity at 11 seconds.

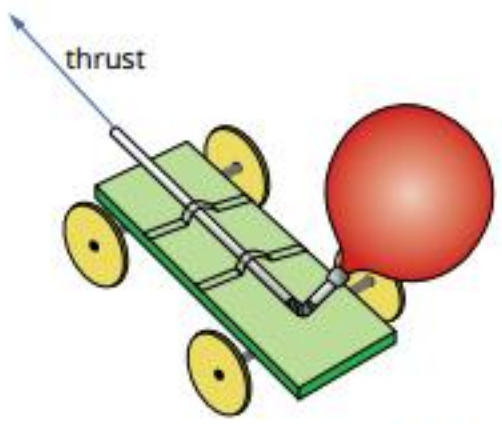
d Determine the conditions that cause the average velocity and instantaneous velocity to be the same.

3 A hot air balloon is floating 800 m above the ground. One of the passengers accidentally drops their phone while taking photos. Calculate the velocity of the phone as it hits the ground, and how long it takes to reach the ground.

4 For the following situations, identify the reaction force to create an action–reaction pair according to the third law of motion. Sketch the force on the drawing.

a sitting in a chair

b balloon-powered car



5 A high-velocity 10.0 g rifle bullet, travelling horizontally, lodges in a 1.00 kg wooden block, at rest on a horizontal, frictionless plane. The block, with the bullet stuck inside, reaches a velocity of 5.00 m s^{-1} in the same direction as the bullet.

a Find the impact velocity of the bullet.

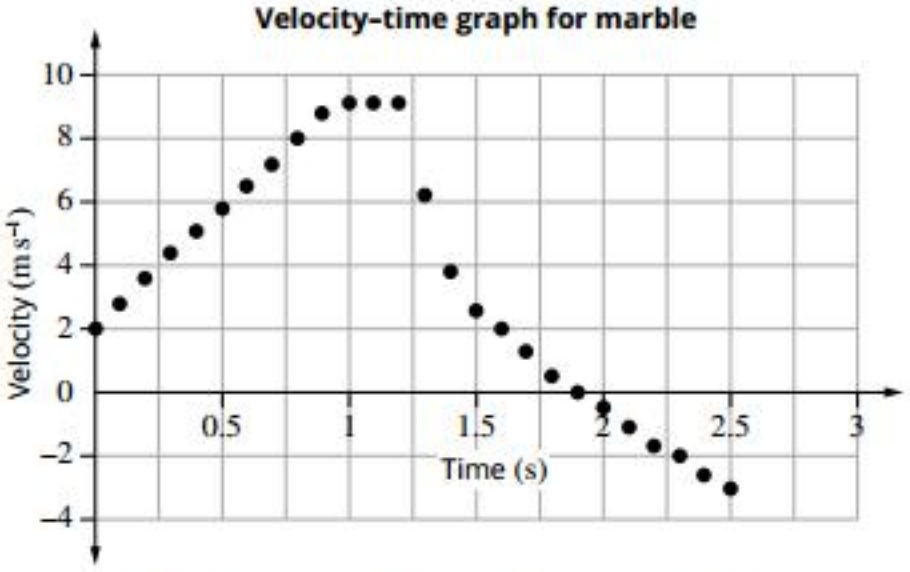
b Calculate the impulse on the wooden block.

6 A dog of mass 20.0 kg is running in the park on a rainy day. The dog runs towards its owner (mass 80.0 kg) at a velocity of 7.0 m s^{-1} and slides into the stationary owner.

a Assuming the dog and owner travel together after the collision, and assuming there is no friction, calculate the velocity of the dog and owner.

b Determine if the collision is elastic or inelastic. Justify your answer.

7 Students measure the velocity of a marble in a straight section of a marble run at 0.1 s intervals. The graph of their results is shown below.



Describe the motion of the marble, including the displacement, velocity and acceleration.

8 Students were conducting an experiment to measure the acceleration due to gravity. They recorded a video of a ball, of mass 500 g, as it was dropped from the second storey. The following data was obtained from the video:

Position (m)	Time (s)
11.4	0
10.616	0.4
8.264	0.8
4.344	1.2
0.07904	1.52

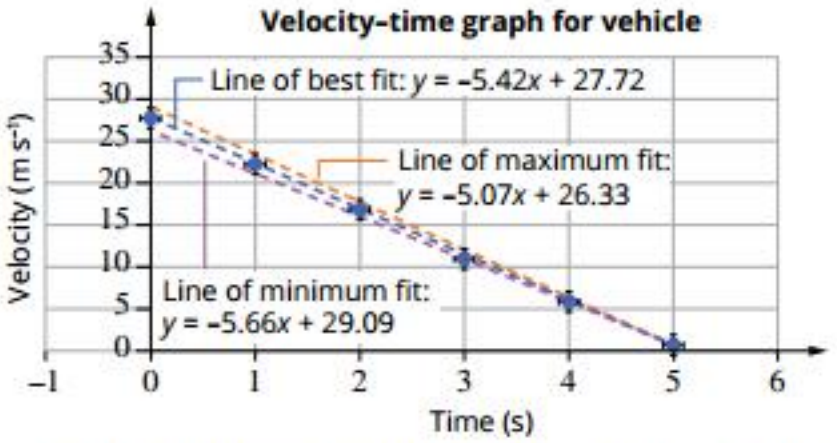
a Plot a graph of position vs time. Infer the type of relationship between position and time from the shape of your graph.

b Linearise the data and graph it.

c Identify a mathematical relationship between displacement and time using the linearised graph.

d Draw a conclusion that quantifies the magnitude of acceleration on the ball. Show your reasoning.

9 An experiment was conducted to measure the change in velocity of a braking vehicle with time. The data was collected and plotted on the graph below

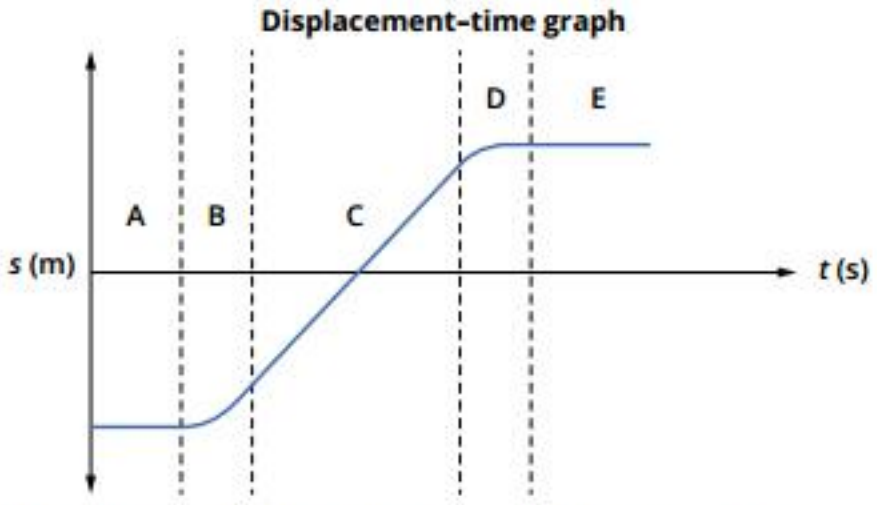


a Identify a mathematical relationship between the velocity of the vehicle and time, including the uncertainty of the gradient and *y*-intercept.

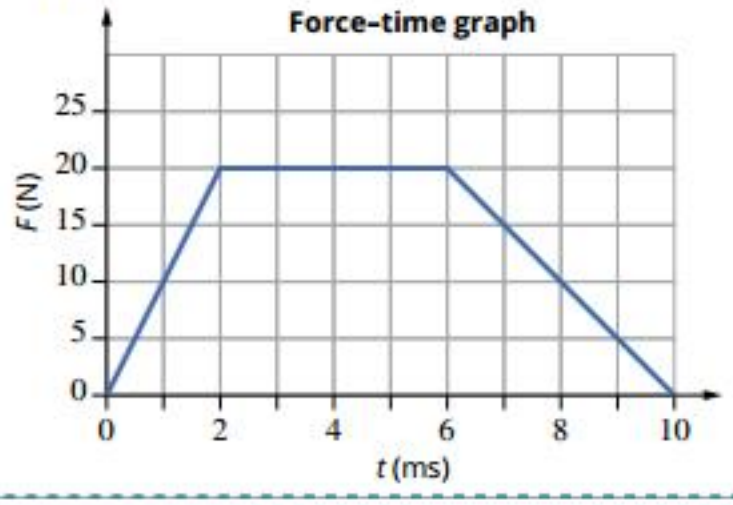
b Describe what the *y*-intercept represents in the experiment

c Draw a conclusion that quantifies the magnitude of the acceleration of the braking vehicle including the absolute and percentage uncertainty in the value you determine. Show your reasoning.

10 A sketch of a displacement time graph is shown below with five distinct sections labelled A to E. Create a sketch of the corresponding velocity-time graph and acceleration-time graph including each of these sections. Values are not required.



11 The force-time graph for an impact is shown below. Analyse the graph to determine the impulse delivered by the impact.

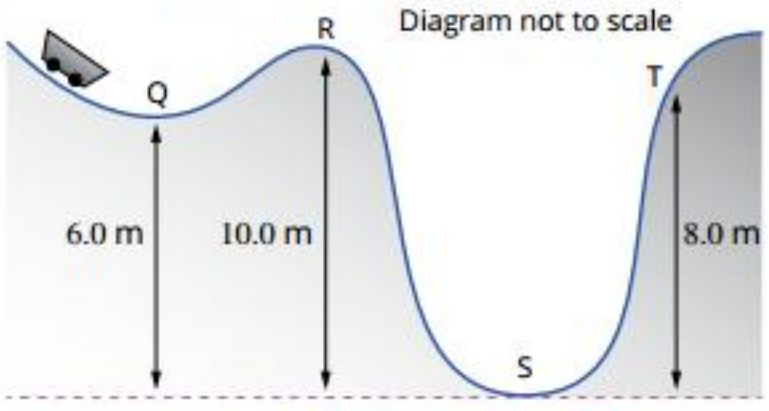


12 A bird has caught a fish and is flying to a nearby tree.

The bird has a mass of 1.4 kg, and the fish has a of mass 500 g. The bird is gliding with a constant velocity of $10\,m\,s^{-1}$ in a positive direction when the fish wriggles free. Immediately after losing the fish, the velocity of the bird is $12\,m\,s^{-1}$ in the same direction.

- **a** Calculate the velocity of the fish the moment after being let go, before accelerating towards the ground.
- **b** The bird and fish are 80.0 m above the ground when the fish wriggles free. Calculate the magnitude of the velocity of the fish when it reaches ground level.
- **c** The fish lands in water, coming to a stop in 0.3 seconds. Calculate the force on the fish during this time.
- **d** Explain how momentum is conserved when the fish lands in the water.

13 The diagram shows a section of roller-coaster track. The mass of an empty carriage is 350 kg. Ignore any effects due to friction. The carriage is momentarily at rest at point R before it rolls towards point S.

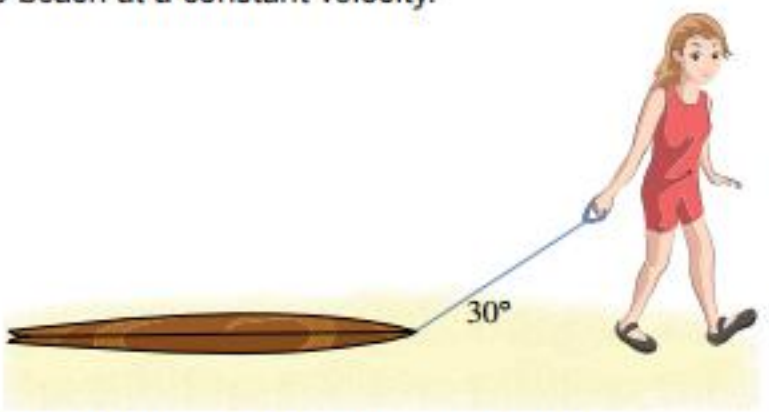


- **a** Calculate the amount of gravitational potential energy the carriage possesses at point R.
- **b** Calculate the amount of kinetic energy the carriage possesses at point R.
- **c** Calculate the amount of kinetic energy the carriage possesses at point S.
- **d** Determine the speed at which the carriage passes through point S.
- **e** The carriage passes point S and heads towards point T. Calculate the speed of the carriage as it passes through point T.
- **f** During another trial run, the carriage travels through point Q with sufficient speed so that it is just able to reach point R. Determine the speed of the carriage at point Q during this trial.

14 An improvement in car safety for drivers has been the introduction of airbags. Explain, with reference to the following concepts, why this is so.

- **a** The first law of motion
- **b** Impulse

15 A young girl was pulling a surfboard of mass 3 kg along the beach at a constant velocity.

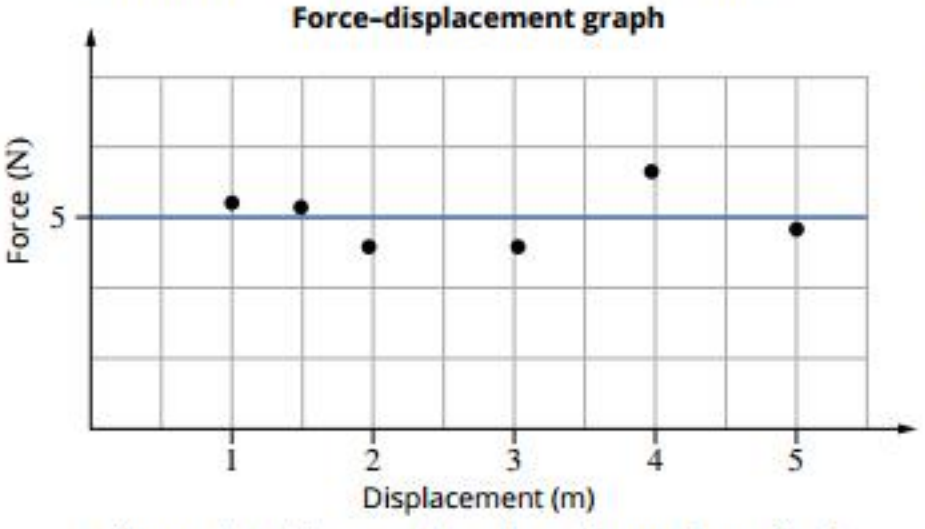


The friction force acting on the surfboard was a constant 9 N.

- **a** Draw a free body diagram of the forces acting on the surfboard.
- **b** Calculate the work required to overcome the friction force as the board travels 5 m.
- **c** Her older sister told her that it is easier to drag a surfboard along its edge. Explain why this is the case.

- **d** Her sister proves it to her by recording the force she applies to move the board 5.0 m. Use her results to calculate the work required to move the surfboard at a constant velocity by dragging it on the side.

Force–displacement graph



- **e** Suggest another way to reduce the work required.

16 Describe a situation when an object would be accelerating without a change in speed.

17 A car speeds up uniformly from 0 to 18 $m s^{-1}$ over 10 seconds and then slows down uniformly to a stop over 5 seconds. Sketch a velocity–time graph of this scenario and use the graph to calculate:

- **a** the acceleration of the car from 0 to 10 seconds
- **b** the acceleration of the car from 10 to 15 seconds
- **c** the total displacement of the car.

18 An apple falls from a branch 5 metres above the ground.

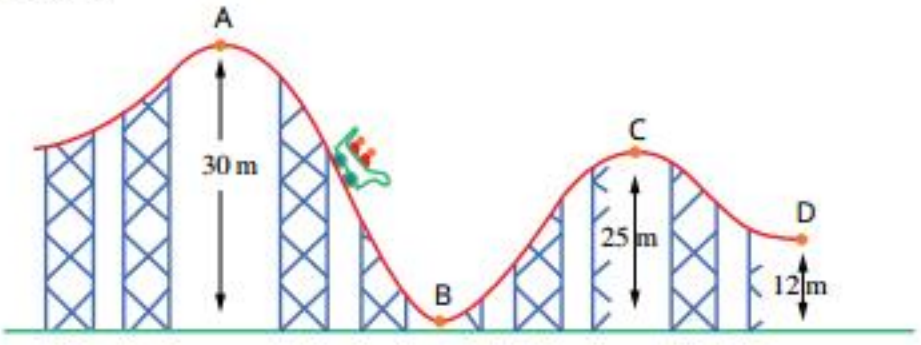
- **a** Calculate the time it takes to reach the ground.
- **b** Calculate the final velocity.
- **c** Create a velocity–time graph and acceleration–time graph of the apple's descent.

19 Chalk is used by rock climbers to reduce sweat and improve their ability to grip their climbing surface. Explain, using a relevant law of motion, why this is an important practice for climbing.

20 Airbags and seatbelts are a common safety feature in modern cars. Explain the purpose of these devices with reference to the forces experienced by an occupant during a collision.

21 In boxing, a jab is a quick, straight punch designed to keep the opponent at a distance. Explain with reference to a relevant physics concept why speed is important when executing a jab.

The following diagram of a roller-coaster relates to questions 22–23.



22 Calculate the speed at points B, C and D, assuming an initial horizontal speed of 4.0 $m s^{-1}$ at point A and ignoring losses to friction and air resistance.

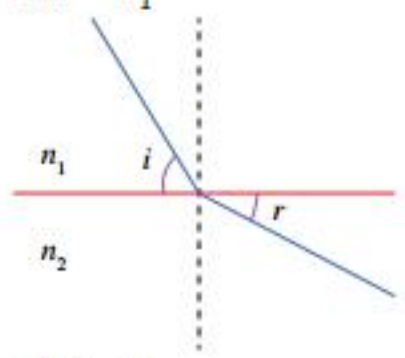
23 Sketch a graph showing how the potential energy, kinetic energy, and total energy change as the cart moves from point A to point D. Exact values are not required. Ignore friction and air resistance.

Topic 2: Waves

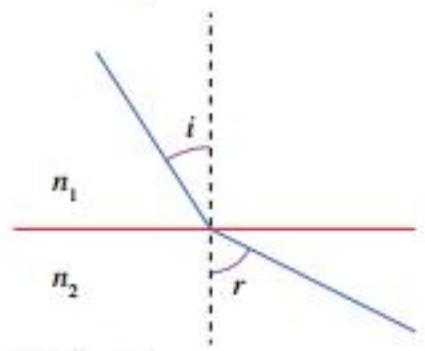
Multiple choice

1 Identify the correct version of Snell's law and the definition of the variables.

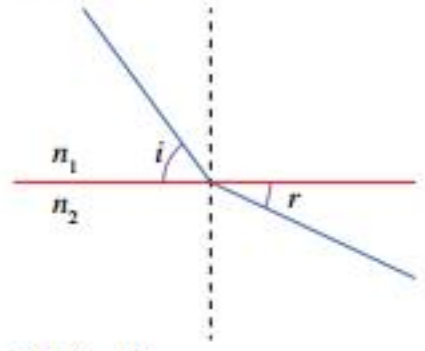
A $\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$



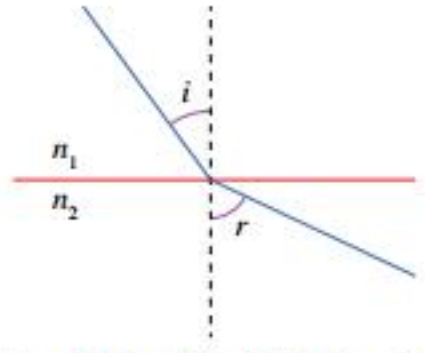
B $\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$



C $\frac{\sin i}{\sin r} = \frac{n_1}{n_2}$



D $\frac{\sin i}{\sin r} = \frac{n_1}{n_2}$



2 State which of the following is transferred by all waves from one point to another.

- **A** matter and information
- **B** energy and matter
- **C** energy
- **D** information and energy

3 According to wave theory, when two crests collide they:
- **A** pass through each other with no visible effect.
- **B** cancel out each other leaving an area of no disturbance.
- **C** superimpose on one another to momentarily create a larger waveform.
- **D** reflect as if each collided with a solid wall.

4 Identify which of the following properties of sound is independent of the source producing the sound.
- **A** frequency
- **B** amplitude
- **C** speed
- **D** intensity

5 An image from a plane mirror is best described as:
- **A** real, upright and enlarged.
- **B** real, inverted and the same size.
- **C** virtual, inverted and enlarged.
- **D** virtual, upright and the same size.

6 Two identical lights are placed on either side of the room. An observer stands 3.0 m from one light and measures the intensity of that light to be $25\,W\,m^{-2}$. The second light bulb has a measured intensity of $12\,W\,m^{-2}$. Calculate the distance from the observer to the second light bulb.
- **A** 4.3 m
- **B** 6.3 m
- **C** 18.8 m
- **D** 1.4 m

7 Identify the list below that contains behaviours of light that can be explained with the wave model of light.
- **A** superposition, photoelectric effect, refraction, interference
- **B** reflection, refraction, polarisation, interference, dispersion, diffraction
- **C** polarisation, momentum, reflection, interference, dispersion
- **D** photoelectric effect, refraction, polarisation, reflection

8 An object is placed at a distance of 5 cm in front of a convex lens with a focal length of 3 cm. The image is:
- **A** real, inverted and enlarged.
- **B** real, inverted and diminished.
- **C** virtual, inverted and diminished.
- **D** virtual, upright and enlarged.

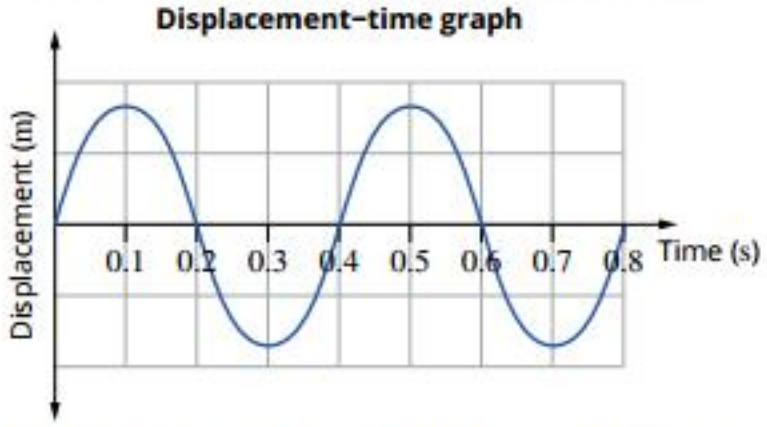
9 In a pipe with two open ends, the fourth harmonic is at 512 Hz. Determine the frequency of the seventh harmonic.
- **A** 1028 Hz
- **B** 3584 Hz
- **C** 128 Hz
- **D** 896 Hz

10 Indicate where an object should be placed for a concave lens to produce an image the same magnitude as the object.
- **A** between the focal point and the lens
- **B** at twice the focal distance
- **C** at infinity
- **D** at the focal point

Short answer

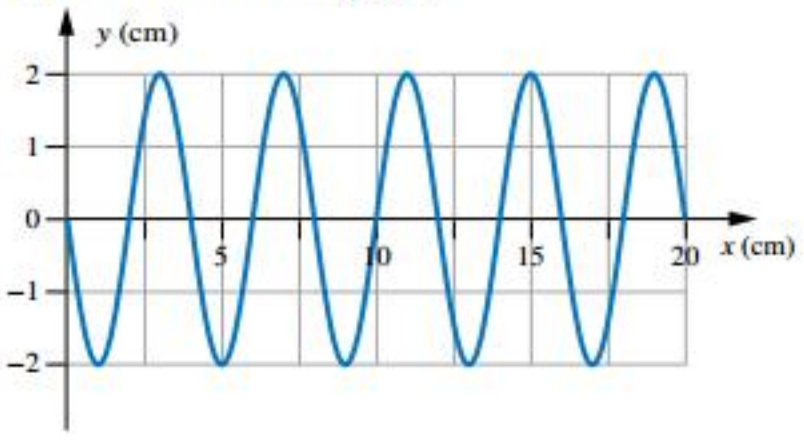
1 Contrast longitudinal waves with transverse waves. Give an example of each.

2 **a** Determine the period of the wave responsible for the motion of the particle depicted on the graph below.



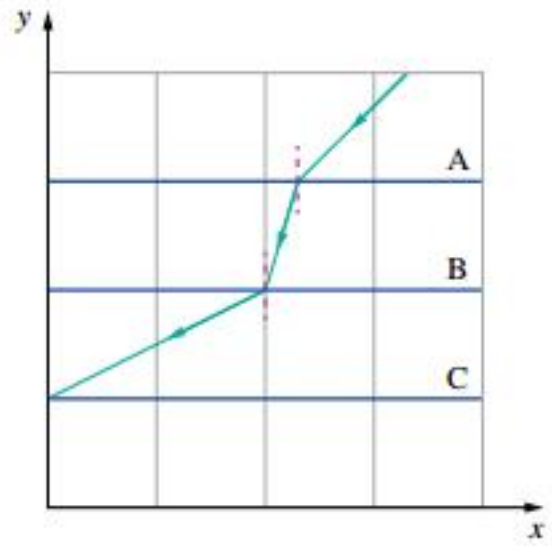
b Calculate the speed of the wave if the wave moves 2.0 m in the time for one period.

3 Determine the wavelength and amplitude of the wave depicted in the following graph.



4 A friend sits stationary on a swing and asks you to push them. Explain how the concept of resonance relates to pushing your friend so the height of swing increases over time.

5 The following diagram shows three different media through which light can pass. The path that a ray of light takes through these three media is also shown. List the media in order from highest refractive index to lowest refractive index.



6 Light travelling in air enters a second medium of refractive index 2.42 at an angle of incidence of 30.0°.

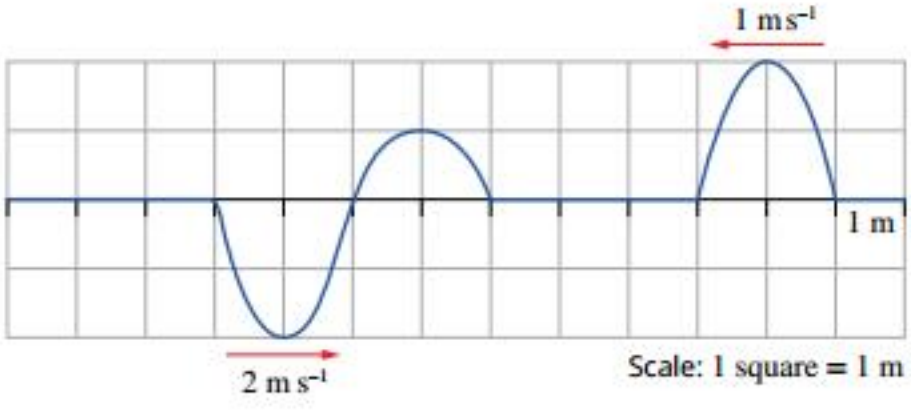
a Determine the angle of refraction.

b Calculate the speed of light in the second medium.

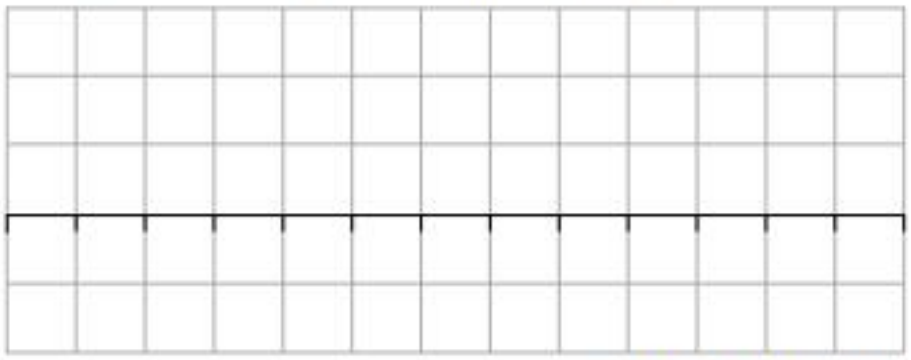
7 When ordinary white light is viewed through a single polarising sheet, the brightness of light passing through to the observer is reduced by about half. A second polarising sheet can be placed on top of the first sheet in such a way as to have no effect on the brightness of the light passing through it. If the second sheet is now rotated 90°, almost no light now passes through to the observer.

Explain these observations using the appropriate physics principles.

8 Two pulses on a string approach each other as shown below.



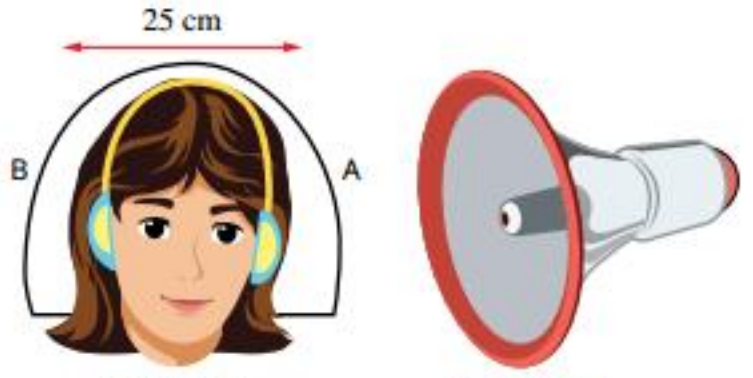
a Copy the grid below and draw, in one colour, the positions of the two individual pulses 2 seconds after their positions shown in the diagram above.

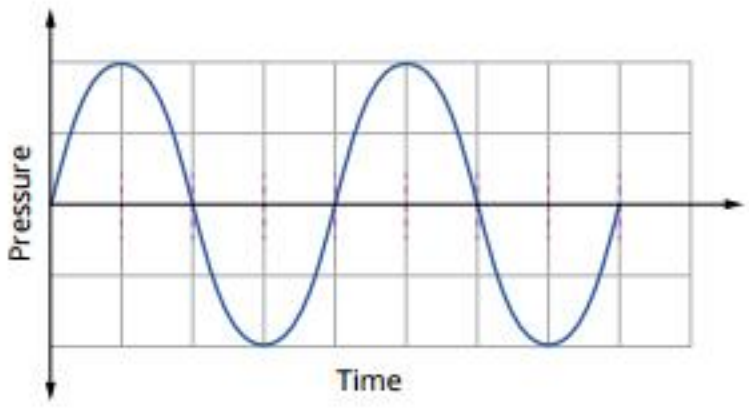


b Then, in another colour, draw the superposition of the two pulses at this time.

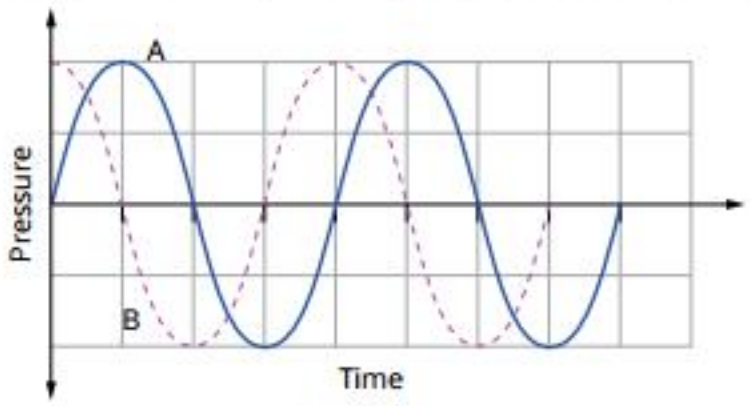
9 Describe the concept of intensity including its relationship with distance and its relationship with amplitude.

10 A simulator of the human head is used to determine the efficiency of hearing aids. The process involves a sound of set frequency being produced from a speaker at one side of the simulator as shown in the diagram. Hearing aid A is closer to the speaker and a display of its reception is given.





a On the same axes, draw the display as it will appear one-quarter of a cycle later.
Hearing aid B is 25 cm further from the speaker than hearing aid A. The graph below indicates the reception from both hearing aids at the same time.



b Calculate the wavelength of the sound.
c Given the speed of sound in air is $340\,m\,s^{-1}$, determine the frequency of the sound.

11 Two circular waves are created in a water tank. The waves are formed exactly in phase and interfere when they meet. At the edge of the tank, sensors detect two kinds of interference patterns in the water: constructive and destructive. The constructive interference occurs when two crests or two troughs meet.
a Explain when destructive interference will occur and describe what it will look like.
b Identify the type of interference the sensors will detect at the very centre of the pattern.
The waves are created at a rate of 50 crests per second and travel with a velocity of $0.60\,m\,s^{-1}$.
c Calculate the wavelength of the waves.
Consider a point X where the sensors detect the second non-central destructive interference pattern.
d Calculate the difference in path length between X and one wave source and X and the other wave source.

12 A string is attached to a ring around a pole so that it is free to move. The other end of the string is fixed. The tension in the string is constant. The effective length of the string is 75 cm and the speed of a wave created in the string is $330\,m\,s^{-1}$.
a Describe natural frequency with respect to this string.
b Calculate the frequency of the fundamental frequency (also known as the first harmonic).
c Calculate the frequency of the third harmonic.
d Calculate the frequency of the next harmonic after the third that the string can produce.

13 A flute, 35 cm in length, is open at both ends. A clarinet, also 35 cm in length, has one open end and one closed end. The speed of sound in air in the instruments is $340\,m\,s^{-1}$.
a Describe how a standing wave is created inside the pipe.
b Sketch the 3rd harmonic in both instruments.
c One of the instruments was measured to have a fundamental frequency of 485 Hz. Determine if the instrument is the flute or the clarinet.
d Explain why the sound of the instruments is loud only when the input vibrations are certain frequencies.

14 A student is designing an experiment to measure the refractive index of an unknown transparent medium, using yellow light.
a Light is often modelled as a wave. Contrast light waves and sound waves.
b Describe the process that causes refraction, using the wave model of light.
c State Snell's law and describe how it can be used to measure an unknown refractive index.
The following results were obtained.

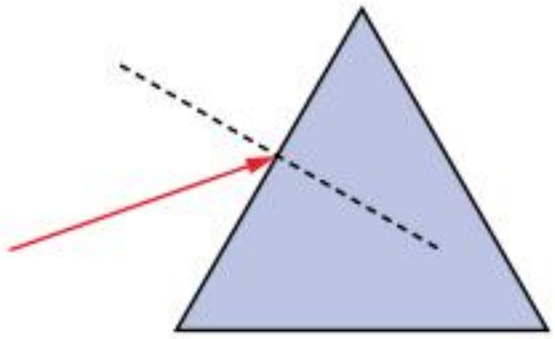
Angle of incidence i (°)	Angle of refraction r (°)
10	6.8
20	13.5
30	20.0
40	26.1
50	31.6
60	36.4

d Use the table of refractive indices of yellow light ($\lambda = 589\,nm$) in different media to identify the material that was being tested.

Material	Refractive index, n
vacuum	1.00
air	1.00
ice	1.31
water	1.33
quartz	1.46
crown glass	1.52
flint glass	1.62
diamond	2.42

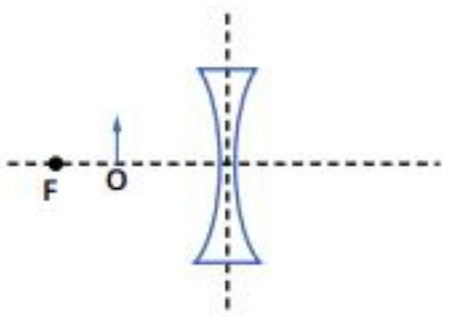
15 Copy and complete the following ray diagrams to describe the image produced by the object (O) in each mirror.

16 a Copy and complete the following ray diagram to describe the path of light through the prism.

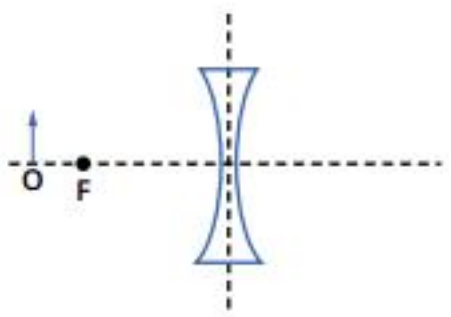


b Copy and complete the following ray diagrams to describe the image produced by the object (O) in each lens.

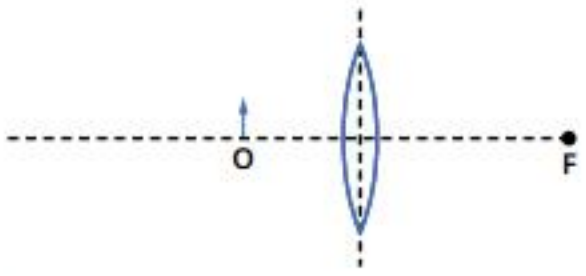
a



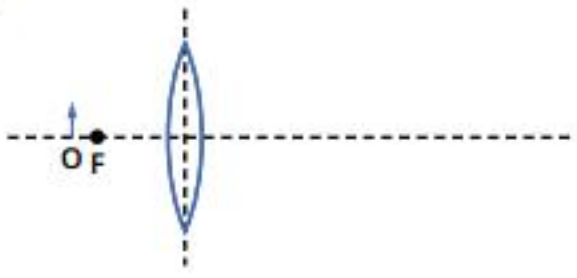
b



c



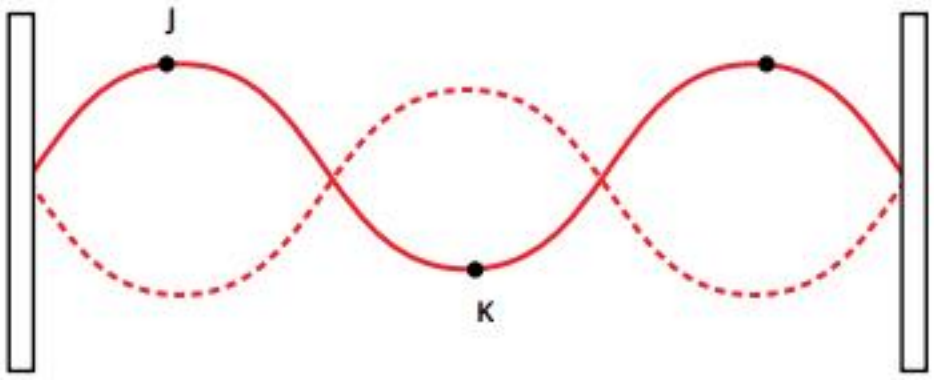
d



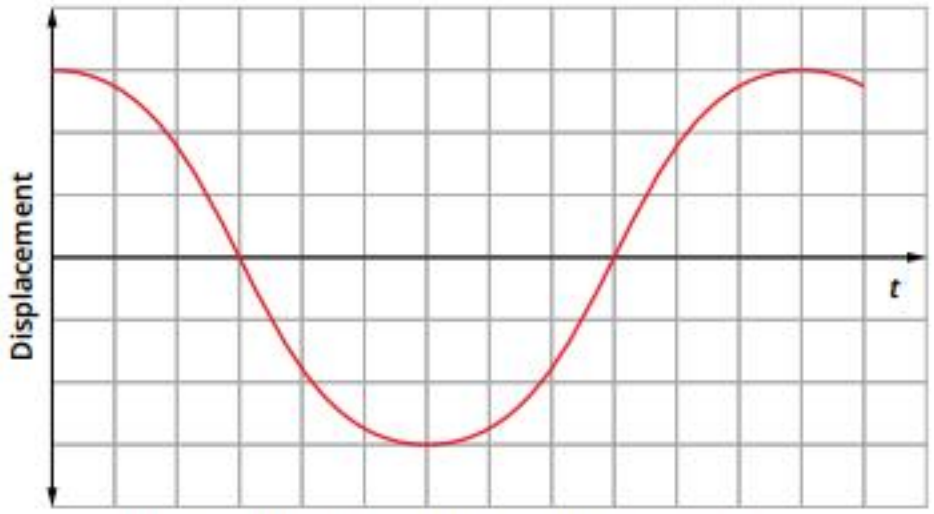
17 An endoscope is a device used in keyhole surgery. This device allows doctors to insert a flexible tube containing optical fibres into a small hole in a patient, allowing them to make observations without the need for larger incisions. Explain, with reference to relevant physics concepts, how it is possible for the endoscopes to transmit a clear image to a doctor even if it is bent within the patient.

18 Why must a wave in a gas be a longitudinal wave?

19 A string is fixed at both ends and a standing wave is formed on the string. J and K are two particles on the string.



The variation with time t of the displacement of particle J is shown below.



Copy the graph into your book, and draw on the same axes the variation in displacement of K.

20 A pipe closed at both ends can be modelled using the same equation as a string (in both cases there are nodes at the ends). This is rarely used for instruments but can be used for investigating how sound behaves inside a closed room, such as a theatre. Judge the validity of modelling a theatre as a pipe closed at both ends.

21 An example of a simple pipe instrument is the thong-o-phone. This instrument is constructed with PVC pipes of differing lengths which are struck on one open end with a thong. Select a simple piece of music (such as hot cross buns) and design a pipe instrument capable of playing the song.

22 With reference to the formulas for pipe instruments, explain why all pipe instruments require some form of tuning.

23 In binoculars, a right-angle triangular prism uses total internal reflection to turn the light rays through 180°. Draw a diagram to show how this is possible.

24 How is the spectrum produced by a diffraction grating different from that produced by the dispersion of light from a triangular prism?

25 How many times further away must a light source be for its intensity to be one hundredth of what it was?

Practical manual

Practical investigations support the development of science inquiry skills and provide students with hands-on experience to deepen their understanding. The following science inquiry investigations offer opportunities for students to engage with practical applications of scientific concepts. These skills involve identifying and posing questions and working to answer them, evaluating claims, investigating ideas, solving problems, reasoning, drawing valid conclusions, and developing evidence-based arguments.

Through these investigations, students will practise writing research questions, planning and conducting experiments, recording information, and reflecting on their processes. They will learn to process, analyse, and interpret evidence, evaluate conclusions and claims critically, and communicate their findings effectively.

Syllabus subject matter

Unit 1: Thermal, nuclear and electrical physics

Practical investigation 1 – Investigate the relationship between heat and temperature change

- Investigate the proportional relationship between heat and temperature change.

Practical investigation 2 – Investigate specific heat capacity of a substance

- Investigate specific heat capacity of a substance.

Practical investigation 3 – Find the resistance of an ohmic resistor and interpreting *V–I* graphs

- Compare characteristics of ohmic and non-ohmic resistors experimentally.
- Interpret graphical representations of electrical potential difference versus electric current data to find resistance using the gradient and its uncertainty.

Unit 2: Linear motion and waves

Practical investigation 4 – Determine acceleration due to gravity and interpret linear motion graphs

- Interpret experimental data to determine the value of acceleration due to gravity on the Earth's surface.
- Interpret linear motion graphs to describe the motion of an object, referring to the
  - intercepts, gradients and uncertainties (using minimum and maximum lines of best fit) of displacement–time and velocity–time graphs
  - areas under velocity–time and acceleration–time graphs using simple geometry.
- Solve problems relating to uniformly accelerated motion in one dimension using $v = u + at$, $s = ut + \frac{1}{2}at^2$, and $v^2 = u^2 + 2as$.

Practical investigation 5 – Investigate displacement–time and velocity–time graphs with uncertainty analysis

- Investigate situations that involve displacement–time and velocity–time graphs.
- Use vertical error bars when plotting data to determine the uncertainty of the gradient and intercepts using minimum and maximum lines of best fit.

Practical investigation 6 – Investigate the refractive properties of different substances

- Investigate the refractive properties of different substances.

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Investigate the relationship between heat and temperature change

Forming and finding

Aim

To investigate the research question: What is the relationship between heat and temperature change? Conduct an experiment to obtain and analyse data on this relationship by:

- plotting a scatter graph (with correct title and symbols, units and labels on the axes)
- formulating the equation of a linear trendline
- interpreting the data/graph to draw a conclusion
- writing a report that uses scientific conventions and language.

Rationale (scientific background to the experiment)

All states of matter—liquid, solid, or gas—are made of moving particles. The average kinetic energy of these particles is related to temperature. The kinetic energy of each of the individual particles cannot be directly measured, so temperature scales, such as the Celsius and Fahrenheit scales, are used to measure temperature.

The thermal energy, or internal energy, of a material includes the kinetic energy of the atoms or molecules as well as the potential energy between them. Heat is a measure of the energy transferred from a hotter material to a cooler material. When you say you are going to 'heat something up', you are causing heat to flow into something to increase the average kinetic energy of its atoms or molecules.

By applying heat to a beaker of water at a constant rate, it is possible to find a relationship between the heat applied (by measuring the time the water is heated) and its temperature.

Timing

60 minutes

The water will take a long time to boil, so this activity should be started at the beginning of the lesson.

Materials

- 2 thermometers or a temperature sensor
- 600 mL beaker
- hotplate
- 250 mL water
- stopwatch
- heat glove or oven mitt
- 2 retort stands and clamps

Safety

- Do not directly touch hot items like the hot plate, beaker, and water.
- Keep the boiling water away from other electrical equipment like a computer.
- Wear a lab coat, goggles and gloves as recommended by your teacher.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

Reflect and check the materials and method for risks
• Consider and account for risks/ethical issues/environmental issues in the materials and method. • Conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook.

1. Turn on the hotplate to commence heating.
2. Part fill the beaker with water (250 mL).
3. Place a thermometer into the beaker and secure it using a retort stand and clamp so that the tip of the thermometer is submerged in the liquid but not touching the wall of the beaker.
4. Place the water-filled 600 mL beaker with thermometer on the hotplate.
5. Record the temperature of the water at 30 second intervals.
6. Monitor the temperature of the water and when it gets to 80°C, stop recording data.
7. With teacher assistance, use the heat glove to remove the beaker from the hotplate.
8. Allow the liquids and hotplate to cool before cleaning up.

Variables

i. Independent: time the sample is on the hotplate
ii. Dependent: temperature of the water
iii. Controlled: mass of water, initial temperature of water, setting on hotplate

Analysing

Raw data

Mass of beaker: _____

Mass of beaker and water: _____

Copy the following table into your book and use it to record all your data.

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Time (s)										
Water temperature (°C)										

Processed data

Reflect and check that your data analysis demonstrates these characteristics

- Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

Reflect and check that your analysis demonstrates these characteristics

- Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

1 Plot your results on a graph, with time on the horizontal axis and temperature on the vertical axis. Label the axes, include units and add a title for your graph.

2 Draw a line of best fit.

Calculations

3 Calculate the gradient of the line of best fit. Using the general equation for a straight line, $y = mx + c$, write an equation for the relationship between time and temperature.

4 Are there any points on your graph that do not fit the trend? Explain why this may have been the case.

5 State the value, units and meaning of the gradient and y-intercept.

6 Compare your graph and equation value with the values obtained by other groups. Are they the same?

Interpreting and evaluating

Conclusion

1 The aim of the experiment was to determine the relationship between temperature and heat by measuring the temperature of a beaker of water as it was heated. Were you able to find a linear relationship between time and temperature?

2 Write a scientific report that describes your experiment, results and conclusions. Refer to Chapter 1 for more information about writing a scientific report.

Evaluation

3 Considering your analysis and conclusion, did the experiment provide an effective method of finding a relationship between the time the water was heated and the temperature of the water?

Improvements

4 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

5 Do you think this methodology could be applied to determine the relationship between temperature and heat for any substances?

6 Identify any limitations to using this method for other substances.

Reflect and check that your evaluation demonstrates these characteristics

- Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
- Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment that are logically derived from the analysis of the evidence.

PRACTICAL INVESTIGATION 2

Investigate specific heat capacity of a substance

Forming and finding

Aim

To investigate the research question: What is the specific heat capacity of a substance, and how can measurement uncertainties associated with mass and temperature be propagated? Additionally, how can the absolute uncertainty of the mean be determined when calculating its value?

Rationale (scientific background to the experiment)

The amount of energy added to (or taken away from) a substance is proportional to the change in its temperature, its mass and its specific heat capacity.

The mathematical relationship between the heat energy transferred, Q, and temperature change, ΔT, for a substance of mass m is given by:

$$Q = mc\Delta T$$

where

Q is the heat energy transferred in joules (J)

m is the mass of material being heated in kilograms (kg)

ΔT is the change in temperature (°C or K)

c is the specific heat capacity of the material ($Jkg^{-1}K^{-1}$).

In this experiment, a metal sample is heated by placing it in a beaker of boiling water. The temperature of the metal will increase as it absorbs energy from the water. The metal sample is then placed in a calorimeter cup and the temperature measured as the water in the cup and the metal sample reach equilibrium.

By measuring the temperature of the water before the metal is added and as it comes to equilibrium, it is possible to find the heat energy given to the water by the metal. Then by measuring the mass of the metal and its change in temperature, it is possible to find its specific heat capacity.

Timing

45 minutes

Materials

- thermometer
- balance (1 per classroom)
- hotplate
- 600 mL beaker
- tongs
- 3 calorimeter cups
- retort stand and clamps
- 1 L water
- metal samples (at least five masses of the same metal)
- 15 cm string for each sample

Safety

- When using the hotplate, be very careful not to burn your hands or fingers.
- Use a 600 mL beaker for boiling water that can withstand high heat, such as a *Pyrex* beaker. Other beakers may shatter when exposed to high heat.
- Boiling water can cause severe burns. Be very careful when using boiling water, and do not carry the beaker without insulated gloves or tongs when it is hot.
- All glass beakers can break when dropped. Be very careful not to drop any of the glassware used in this lab. If an accident does occur, follow the proper cleaning and disposal procedure instituted by your teacher.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

Reflect and check the materials and method for risks
• Consider and account for risks/ethical issues/environmental issues in the materials and method. • Conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook.

1 Create a hot-water bath by filling the beaker $\frac{3}{4}$ full of water and placing the beaker on the hotplate.

Note: To speed up this step, use a kettle to boil the water first.

2 Set the hotplate temperature to boil the water in the beaker.

3 Use the balance to measure the mass of each calorimeter cup, and its uncertainty, and then record this in the data analysis section.

4 Add equal amounts of water to the calorimeter cups (so they are approximately $\frac{3}{4}$ full) and record the mass of each calorimeter cup and water, with its uncertainty, in the data analysis section.

Note: The calorimeter cups and beaker are only $\frac{3}{4}$ full so that the water level does not spill over the edge of the cup or beaker when you submerge the metal sample.

5 Record the mass of each metal sample, and its uncertainty, in the data analysis section.

6 Tie a 15 cm piece of string to each metal sample. Tie the other end of the string to a retort stand so that the metal sample is suspended in the water rather than touching the bottom of the beaker.

7 Check the temperature in each calorimeter to ensure it is room temperature and record this value in the data analysis section as the initial temperature of the water in the calorimeters.

8 Allow the hot-water bath to come to a boil.

9 Place the first metal sample in the hot-water bath, and allow it to equilibrate for 5 to 10 minutes.

10 Use the thermometer to measure the temperature of the hot water, and record this and its uncertainty.

11 Place the thermometer in the first calorimeter cup.

12 Quickly but carefully transfer the first metal sample from the hot-water bath to the calorimeter cup.

13 Place the second metal sample in the hot-water bath.

14 Check the temperature in the calorimeter cup three times at 30-second intervals. Once the temperature in the calorimeter reaches equilibrium (remains constant), make a note of the temperature and its uncertainty.

15 Place the thermometer in the second calorimeter cup.

16 Quickly but carefully transfer the second metal sample from the hot-water bath to the calorimeter cup.

17 Place the third metal sample in the hot-water bath.

18 Check the temperature in the calorimeter cup three times at 30-second intervals. Once the temperature in the calorimeter reaches equilibrium (remains constant), make a note of the temperature and its uncertainty.

19 Place the thermometer in the third calorimeter cup.

20 Quickly but carefully transfer the third metal sample from the hot-water bath to the calorimeter cup.

21 Check the temperature in the calorimeter cup three times at 30-second intervals. Once the temperature in the calorimeter reaches equilibrium (remains constant), make a note of the temperature and its uncertainty.

22 Repeat the process for the other two samples.

23 Make sure your hotplate is turned off, and carefully clean up as instructed by your teacher.

Variables

i Independent: mass of the metal samples

ii Dependent: change in temperature of the water in the calorimeter cup

iii Controlled: initial temperature of the metal, initial temperature of the water, type of metal sample, surrounding temperature, and mass of the water

Analysing

Raw and processed data

Reflect and check that your data analysis demonstrates these characteristics
• Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data. • Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

After recording temperature data for all five of your samples, calculate the change in temperature, ΔT, for both the calorimeter water and the metal sample.

Then calculate the heat transferred to the calorimeter water by the metal sample using $Q = mc\Delta T$ and $c_{water} = 4200\,J\,kg^{-1}\,°C^{-1}$. For an example of the calculation see Worked example 2.6.1 on page 32, then use that value of Q with $Q = mc\Delta T_{metal}$ to find the specific heat capacity of the metal.

Remember to propagate your uncertainties through your calculations to give an uncertainty with each specific heat capacity calculated. See Chapter 1 or your teacher for guidance.

Sample 1

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 2.1 Mass and temperature data

Sample 1	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Sample 2

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 2.2 Mass and temperature data

Sample 2	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Sample 3

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 2.3 Mass and temperature data

Sample 3	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Sample 4

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 2.4 Mass and temperature data

Sample 4	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Sample 5

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 2.5 Mass and temperature data

Sample 5	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Analysis

Reflect and check that your analysis demonstrates these characteristics

- Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

1 Calculate the specific heat capacity, c, of the metal, using $Q = mc\Delta T$ for each sample. Enter these values in the table below.

TABLE 2.6 Combined results from 5 trials

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Specific heat capacity						
Uncertainty in specific heat capacity						

2 Take the average of these 5 samples to find a specific heat capacity of the metal. To calculate the absolute uncertainty of the mean use:

uncertainty in $c = \pm \frac{c_{max} - c_{min}}{2}$ (see Chapter 1).

3 Explain some of the factors that might have caused your calculated values for specific heat capacity to be inaccurate and how these factors could be avoided.

Interpreting and evaluating

Conclusion

1 The aim of the experiment was to determine the specific heat capacity of a metal sample. Were you able to find a value for it?

2 Use Table 2.4.1 on page 21 to identify the specific heat capacity of the metal. How does your experimental value compare to this? Is the value given in Table 2.4.1 within your uncertainty range?

3 Can you identify the type of metal from its specific heat capacity?

Evaluation

4 Considering your analysis and conclusion, did the experiment provide an effective method of finding the specific heat capacity of the metal?

5 Was the level of uncertainty that you calculated in Question 2 reasonable?

Improvements

6 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

7 Do you think this methodology could be applied to determine the specific heat capacity of any metal?

8 Identify any limitations to using this method for other metals.

Reflect and check that your analysis demonstrates these characteristics

- Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
- Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment that are logically derived from the analysis of the evidence.

PRACTICAL INVESTIGATION 3

Find the resistance of an ohmic resistor and interpreting *V–I* graphs

Forming and finding

Aim

To investigate the research question: How can the resistance of an ohmic resistor be determined by measuring the current through it and the potential difference across it? Additionally, how can *V–I* graphs be interpreted to find resistance, and what modifications to the method used in class could improve the outcome? Collect sufficient data with at least five variations of the independent variable and three repetitions of each variation.

Rationale (scientific background to the experiment)

The voltage, V, across an ohmic resistor and the current, I, through it are related to its resistance, R, by the linear relationship Ohm's law, $V = IR$. This can be rearranged to $I = \frac{V}{R}$. The resistance is the inverse of the gradient of the line in a graph of the current drawn by a resistor when the potential difference is varied.

This experiment requires correct use of a voltmeter and ammeter.

Timing

30 minutes

Materials

- variable power supply
- connecting wires
- switch
- Ohmic resistor (200Ω or 2kΩ)
- DC voltmeter (0–10V) or voltage sensor
- DC ammeter (0–1A) or current sensor

Safety

The voltmeter and ammeter must be connected correctly; in particular, make sure that the ammeter is connected in series to avoid damaging it and the voltmeter is connected in parallel across the resistor.

An appropriately sized resistor should be chosen to keep the current in the circuit small, otherwise the current will burn out the resistor and might cause a fire.

Method

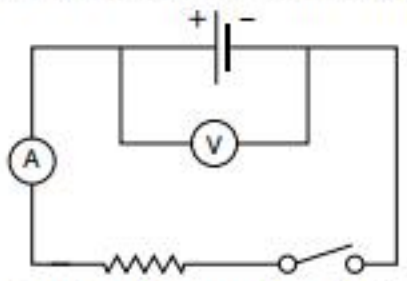
Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

Reflect and check the materials and method for risks

- Consider and account for risks/ethical issues/environmental issues in the materials and method.
- Conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook.

1 Connect the circuit as shown in the diagram below.



2 For a range of voltmeter readings (such as 0, 2, 4, 6, 8 and 10V), close the switch and take the ammeter reading. Include the uncertainty for each measurement.

3 Record the results in a table.

4 Repeat the same measurements two more times in order to obtain an average.

Variables

i Independent: voltage

ii Dependent: current

iii Controlled: resistance

Analysing

Raw data

TABLE 3.1 Measured current for different potential differences

Measured voltage (± _____V)	Measured current (± _____ A)			
	Trial 1	Trial 2	Trial 3	Average
0				±
2				±
4				±
6				±
8				±
10				±

Reflect and check that your data analysis demonstrates these characteristics

- Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

Reflect and check that your analysis demonstrates these characteristics

- Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

1 Plot your results, including error bars, on a graph, with the independent variable, *V*, on the horizontal axis and the dependent variable, *I*, on the vertical axis. Take care with units and check that the units of current are in A, not mA.

2 Draw a line of best fit, including minimum and maximum lines.

Calculations

3 Calculate the gradient of the line of best fit. Use this to find the resistance of the resistor and its uncertainty. Remember that the gradient = $\frac{1}{R}$.

4 Compare this to Ohm's law to find the resistance of the resistor.

5 Calculate the uncertainty in the gradient to find the uncertainty of the resistance.

6 Are there any points on your graph that do not fit the trend? Explain why this may have been the case.

7 Compare your value for resistance with the values obtained by other groups who used the same resistor. Are they the same? Did the other groups use the same values of potential differences as their independent variable?

8 Compare your graph to the graphs drawn by other groups who used different resistors. What do you notice about the shape of the graphs?

9 Would you expect the graphs to be the same or different? Why?

Interpreting and evaluating

Conclusion

1 The aim of the experiment was to determine the resistance of an ohmic resistor by varying the potential difference across it and measuring the current it drew. Were you able to find a single value for the resistance of the resistor?

2 Use the coloured bands on the resistor to identify its resistance. How does your experimental value compare with this?

Evaluation

3 Considering your analysis and conclusion, did the experiment provide an effective method of finding the resistance of the resistor?

4 Was there a reasonable level of uncertainty in your calculations for the resistors?

Improvements

5 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

6 Do you think this methodology could be applied to determine the resistance of any component in a circuit, for example a light bulb?

7 Identify any limitations to using this method for other resistors.

Reflect and check that your evaluation demonstrates these characteristics

- Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
- Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment, which are logically derived from the analysis of the evidence.

PRACTICAL INVESTIGATION 4

Determine acceleration due to gravity and interpret linear motion graphs

Forming and finding

Aim

To investigate the research question: What is the value of acceleration due to gravity on the Earth's surface, and how can it be determined from experimental data and linear motion graphs? Conduct an experiment to verify this value, interpret the data, and suggest modifications to improve the method used in class. Collect sufficient data with at least five variations of the independent variable and three repetitions of each variation, and consider safety throughout the process.

Rationale (scientific background to the experiment)

The displacement, s, of an object travelling in a straight line can be described by the equation $s = ut + \frac{1}{2}at^2$, where u is its initial velocity, t is time and a is acceleration. For an object falling vertically, from rest, the acceleration of the object will be the acceleration due to gravity, g, near Earth's surface if the effects of air resistance are ignored. By collecting data of the time taken for the object to hit the ground when it falls from a height s, with an initial velocity of zero, the acceleration due to gravity can be found from the gradient of the line. By graphing s versus t squared, the gradient of the line is $\frac{1}{2}a$.

As mentioned in Module 6.5, air resistance will oppose the motion of a falling object. Therefore, small objects that minimise air resistance, such as a coin or a ball bearing, should be chosen for this experiment.

Timing

45 minutes

Materials

- $2 coin, ball bearing or other small object to drop
- smartphone or tablet with a sound recording app such as Audacity
- long tape measure

Safety

- Be careful that the area is clear when the object is being dropped, especially if it is dropped from a window, stairwell or other large height. Make sure the object is not too heavy, to avoid damaging the floor.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

Reflect and check the materials and method for risks

- Consider and account for risks/ethical issues/environmental issues in the materials and method.
- Conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook.

1. Decide on five different heights from which to drop the object. The minimum height should be 1 m; otherwise, it will be too difficult to accurately record the time taken for the object to fall. Also try larger heights (for example, from a stairwell or window) but bear in mind that you need to accurately measure the distance the object falls.
2. Nominate one person to operate the recording software, and another to drop the object. Open a new software document and start recording. The student operating the recording software should count down to the drop ('three, two, one, drop'). Make sure that the instruction to drop the object is louder than the countdown and can be picked up by the microphone (it should register as a peak on the software). Drop the object.
3. The software should then register another peak when the object hits the ground. Make sure the ground is hard (not carpet or grass) so that the object will make a sound when it hits it. It is important to limit background noise so the software can detect the sound. Stop recording as soon as the object hits the ground.
4. Note the results in a table for the distance the object has fallen and the time it has taken, with the uncertainty for each measurement. The uncertainty in the measurement for the distance (measured by a tape measure or metre rule) is likely to be ±1 cm; although the tape measure is precise to 1 mm, it is unlikely that you will be able to measure the height that accurately. The uncertainty in the measurement for the time will depend on the software; most can record time to ±0.01 s, so the total uncertainty in the time measurement would be ±0.02 s. Refer to Chapter 1 for a reminder of how to determine uncertainties in measurement.
5. Repeat the same measurements two more times in order to obtain an average.

Variables

i Independent: height the object is dropped from, *s*

ii Dependent: time taken for the object to fall, *t*

iii Controlled: starting velocity, mass, volume and shape of object being dropped

Analysing

Raw and processed data

TABLE 4.1 Measured time taken for object to drop from different heights

Measured height (± _____ m)				Measured time (± _____ s)			
Trial 1	**Trial 2**	**Trial 3**	**Average**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
			±				±
			±				±
			±				±
			±				±
			±				±

TABLE 4.2 Time taken to drop, squared

Measured height (± _____ m)				Time taken squared (t^2) (± _____ s)			
Trial 1	**Trial 2**	**Trial 3**	**Average**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
			±				±
			±				±
			±				±
			±				±
			±				±

Reflect and check that your data analysis demonstrates these characteristics

- Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

1 Plot the results from Table 4.1 on a graph, with the variable *t* on the horizontal axis and the variable *s* on the vertical axis. Include error bars for each point plotted.

2 Plot the results from Table 4.2 on a graph, with t^2 on the horizontal axis, and *s* on the vertical axis. Include error bars for each point plotted.

3 Draw a line of best fit and find its gradient. Use your error bars to draw a minimum and a maximum line. As t^2 is on the horizontal axis and *s* is on the vertical axis, the gradient will be equal to $\frac{1}{2}g$. Use the minimum and maximum lines to find the uncertainty of your value for the gradient to get the uncertainty for your value of the acceleration due to gravity.

4 Are there any points on your graph that do not fit the trend? Explain why this may have been the case.

5 Compare your value for *g* with the values obtained by other groups. Are they the same? Did other groups use the same values for height?

6 Compare your graph to the graphs drawn by other groups who dropped different objects. What do you notice about the shape of the graphs?

7 Would you expect the graphs to be to same or different? Why?

Reflect and check that your analysis demonstrates these characteristics

- Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

Interpreting and evaluating

Conclusion

1 The aim of the experiment was to determine the value of the acceleration due to gravity by dropping an object from different heights and measuring the time it took to drop to the ground. Were you able to find a single value for the acceleration due to gravity? (Hint: calculate your percentage error.)

2 Look up the value of acceleration due to gravity at Earth's surface. How does this compare with your calculated value? Does it lie within your uncertainty range? (Hint: calculate your percentage error.)

Evaluation

3 Why was it useful to draw a graph using t^2 instead of *t*?

4 Considering your analysis and conclusion, did the experiment provide an effective method of finding the acceleration due to gravity?

5 Was the level of uncertainty that you calculated in your analysis reasonable?

Improvements

6 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced. What were the sources of uncertainty, and which sources contributed most to the uncertainty in the final value?

Extension

7 Would this experiment work using any object?

8 Identify any limitations to using this method for other objects.

9 Would this experiment work if you threw the object upwards and measured the time it took to return to your hand?

Reflect and check that your evaluation demonstrates these characteristics
• Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis). • Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data. • Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment that are logically derived from the analysis of the evidence.

Investigate displacement–time and velocity–time graphs with uncertainty analysis

Forming and finding

Aim

To investigate the research question: How can displacement-time and velocity-time graphs be constructed and interpreted to analyse motion, including determining average velocity and acceleration? Conduct an experiment to create these graphs from data, incorporating uncertainty analysis with horizontal and vertical error bars to assess the uncertainty of gradients and intercepts. Compare graphs for students moving at different speeds over a set distance.

Rationale (scientific background to the experiment)

The following equations describe motion in a straight line with constant acceleration:

- The velocity of an object is the rate at which displacement changes, so the velocity can be found by graphing the displacement of the object against time. The velocity can then be found as the gradient of the line of best fit.
- Similarly, the acceleration of an object can be found as the rate of change of velocity; it is the gradient of a graph of velocity against time.

Timing

45 minutes

Materials

- 50 m running track or 50 m distance marked on sports oval
- 6 stopwatches
- 5 volunteers to run
- video camera, tripod and software (if possible, 5 cameras)
- skateboard/scooter and bicycle

Safety

Make sure there is enough space at the end of the measured distance for the participants to slow down safely.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

Reflect and check the materials and method for risks

- Consider and account for risks/ethical issues/environmental issues in the materials and method.
- Conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook.

1 Position two people at the end of the track, where the participants will finish. One should have a stopwatch, the other a video camera. The student with the video camera should set it up so that the camera is pointing straight along the finish line. Position other students with stopwatches and video cameras/smartphones at 10 m, 20 m, 30 m and 40 m along the track.

2 Get the person with the stopwatch at the finishing line to give a signal for the walker to start. Each student should start their stopwatch. Stop each stopwatch when the walker crosses each line.

3 Set the video camera running when the walker starts walking. Keep the camera pointing along the finish line so that it will record the walker crossing the line, but not their whole walk.

4 Note the results for distance travelled and time taken in a table, with the uncertainty for each measurement. The stopwatch will typically have a precision of 0.01 s, but you will need to factor reaction times into your uncertainty—0.1 s to 0.2 s would be reasonable. The uncertainty in measuring the distances is likely to be 0.1 m. Refer to Chapter 1 for a reminder of how to determine uncertainties in measurement.

5 Repeat these steps for the student running at a medium jog and a flat-out sprint.

6 Repeat this for a student on a skateboard or scooter, and riding a bicycle. Make sure they start from rest (so they are not moving before the signal is given).

7 Repeat each measurement two more times to obtain an average. (You may need to wait for the participants to catch their breath between runs.)

Variables

i Independent: the distance from the start to the end of the track, s

ii Dependent: time taken to walk/run/ride the distance, t

iii Controlled: starting velocity, u

Analysing

Raw and processed data

TABLE 5.1 Measured time taken to walk, run or ride 50 m at 10 m intervals

	Measured time (± ___ s)				
	10 m	20 m	30 m	40 m	50 m
walk					
jog					
sprint					
skateboard/ scooter					
bicycle					

Calculate the velocity for each stage of the walk, run or ride. To do this, use:

$$\text{Velocity per stage} = \frac{\text{distance travelled per stage}}{\text{time taken per stage}}$$

For example:

$$\text{Velocity between 10 m and 20 m} = \frac{20\,\text{m} - 10\,\text{m}}{\text{time taken between 10 and 20 m}}$$

TABLE 5.2 Velocity for each stage

	Velocity (± ___ ms^{-1})				
	0–10 m	11–20 m	21–30 m	31–40 m	41–50 m
walk					
jog					
sprint					
skateboard/ scooter					
bicycle					

Reflect and check that your data analysis demonstrates these characteristics

- Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

1 Plot the results for displacement against time on a graph, with the independent variable t on the horizontal axis, and the dependent variable s on the vertical axis. Include error bars for each point plotted.

2 Draw a line of best fit and find its gradient. Use your error bars to draw minimum and maximum lines. As t is on the horizontal axis and s is on the vertical axis, the gradient will be equal to $\frac{\Delta v}{\Delta t}$ (that is, the average velocity of the walker, runner or rider, v_{av}). Use the minimum and maximum lines to find the uncertainty of your value for the gradient to get the uncertainty for your value of v_{av}. Refer to Chapter 1 for more guidance if necessary.

3 Plot the results for velocity against time on a graph, with t on the horizontal axis, and v on the vertical axis. Include error bars for each point plotted.

4 Draw a line of best fit and find its gradient. Use your error bars to draw minimum and maximum lines. As t is on the horizontal axis and v is on the vertical axis, the gradient will be equal $\frac{\Delta s}{\Delta t}$ (that is, the average acceleration of the walker, runner or rider, a_{av}). Use the minimum and maximum lines to find the uncertainty of your value for the gradient, to get the uncertainty for your value of a_{av}.

5 Are there any points on your graphs that do not fit the trend? Explain why this might be the case.

6 Compare your value for v_{av} and a_{av} with the values obtained by other groups. Are they the same? What does a gradient of zero represent for the velocity versus time graph? What does this mean that the volunteer was doing?

7 Compare your graphs to the graphs drawn by other groups with different participants. What do you notice about the shapes of the graphs?

8 Would you expect them to be to same or different? Why?

9 Where does your line of best fit intercept the horizontal and vertical axes? As your runner started from rest, where would you expect it to cross the axes? What can the intercept tell you about the uncertainties in your measurements?

10 Find the area under the velocity–time graph to calculate the distance travelled. How does this compare with the known length of the track?

Reflect and check that your analysis demonstrates these characteristics
• Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis. • Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships. • Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

Reflect and check that your evaluation demonstrates these characteristics
• Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis). • Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data. • Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment that are logically derived from the analysis of the evidence.

Interpreting and evaluating

Conclusion

1 The aim of the experiment was to determine the average velocity and acceleration of a walker, runners and students on a scooter/skateboard and bicycle by analysing displacement–time and velocity–time graphs. Were you able to find a single constant value for the velocity and acceleration?

Evaluation

2 Considering your analysis and conclusion, did the experiment provide an effective method of finding the average velocity and average acceleration?

3 Was the level of uncertainty that you calculated in part 9 of Analysis reasonable?

Improvements

4 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced. What were the sources of uncertainty, and which ones contributed most to the uncertainty in the final value?

Extension

5 Would this experiment work using any distance or any method of travel?

6 Identify any limitations to using this method for other distances.

7 Would this method work for calculating the average velocity if the runner completed a whole lap of a running track? What might you need to measure instead of displacement? What value would that give you instead of average velocity?

PRACTICAL INVESTIGATION 6

Investigate the refractive properties of different substances

Forming and finding

Aim

To investigate the research question: How do the refractive properties of various substances compare, and what is their relative refractive index with respect to air?

Rationale

When light passes from one transparent medium to another, the rays bend or refract. The law of refraction (Snell's law) states that:

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

where

i is the angle of incidence relative to the normal

r is the angle of refraction relative to the normal.

n_2 is the index of refraction for the refracted ray

n_1 is the index of refraction for the incident ray

The relative refractive index is the ratio $\frac{n_2}{n_1}$.

Timing

45 min

Materials

- light box
- rectangular prisms of clear glass and/or Perspex
- semicircular prisms of clear glass and/or Perspex
- plain paper
- ruler and protractor

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

Reflect and check the materials and method for risks
• Consider and account for risks/ethical issues/environmental issues in the materials and method. • Conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook.

A Rectangular prism

1 Place a glass block on a piece of plane paper and draw around its outline with a sharp pencil. Turn on the light box and adjust it to produce a single, thin beam of light incident to the glass block, as shown in the diagram.

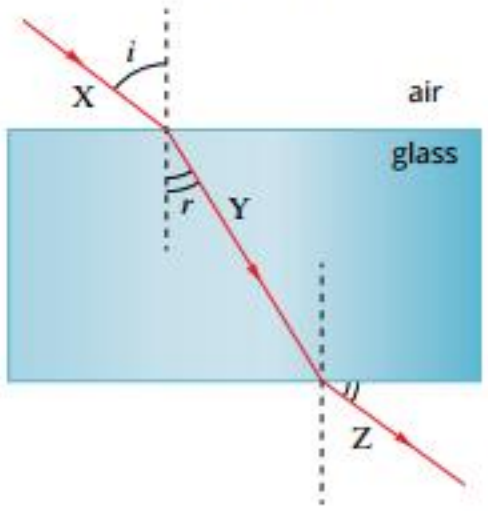


FIGURE 6.1

2 Mark a point along the incident beam, X, the point where it intersects the glass block, Y, and the point where it leaves the glass block and re-enters the air, Z.

3 Join the points X to Y and Y to Z. Use a protractor to draw the normal to the block at point Y. Record both the incident angle (i) and refracted angle (r).

4 Repeat steps 1–3 for at least three other values of i.

5 Repeat the procedure for other materials. For example, Perspex, and different types of glass.

B Semicircular prism

1 Place a semicircular glass block on a clean piece of plane paper. Turn on the light box and adjust it to produce a single, thin beam of light incident on the centre of the straight edge of the prism. Trace the outline of the glass block with a sharp pencil, as shown in the diagram.

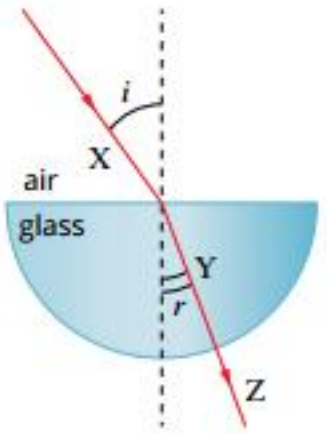


FIGURE 6.2

2 Mark positions X, Y and Z as shown in the diagram above. Join the points X to Y and *Y* to Z. Use a protractor to mark the normal and measure the incident angle *i* and the refracted angle *r*.

3 Repeat for different values of *i* and for different materials (if available).

Variables

i Independent: incident angle

ii Dependent: angle of refraction

iii Controlled: prism material

Analysing

Raw and processed data

1 Record your results in tables 6.1 and 6.2.

TABLE 6.1 Part A: Rectangular prism

i	*r*	sin *i*	sin *r*	Uncertainty in *i*	Uncertainty in *r*	Uncertainty in sin *i*	Uncertainty in sin *r*

TABLE 6.2 Part B: Semicircular prism

i	*r*	sin *i*	sin *r*	Uncertainty in *i*	Uncertainty in *r*	Uncertainty in sin *i*	Uncertainty in sin *r*

2 Note that the uncertainty in sin *x* is given by cos *x* multiplied by the uncertainty in *x* (in radians).

3 Plot your results, including error bars, on a graph, with sin *i* on the horizontal axis and sin *r* on the vertical axis. Label the axes, include units and add a title for your graph.

4 Draw a line of best fit and find its gradient. Use your error bars to draw a minimum and a maximum line.

5 Calculate the uncertainty in the gradient to find the uncertainty of the index of refraction, *n*.

6 Are there any points on your graph that do not fit the trend? Explain why this may have been the case.

7 What factors contribute the most to the uncertainty in *n* and how they can be reduced?

Processed data

Reflect and check that your data analysis demonstrates these characteristics

- Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

Reflect and check that your analysis demonstrates these characteristics

- Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

Interpreting and evaluating

Conclusion

1 Summarise your values for the relative refractive index of each prism and material you have used. Compare your results and comment on the reliability of each method.

Evaluation

2 The incident ray is in the same plane as the drawing paper. Determine whether or not the refracted ray is in the same plane.

3 Identify the advantages of using a semicircular prism.

4 Determine whether the relative refractive indices of air–glass and air–Perspex are the same.

Improvements

5 Assuming the opportunity arose to repeat the experiment, identify the steps or processes you would do differently.

Include in your answer:

- the new methodology and contrast the results from this approach with the initial experiment
- the skills you used to perform the tasks and explain improvements that could be achieved
- methods by which the collection of data could be made more reliable and the uncertainty reduced.

Extension

6 Investigate refraction in a practical context, such as droplets of water or fibre optics.

Reflect and check that your evaluation demonstrates these characteristics

- Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
- Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment which are logically derived from the analysis of the evidence.

References

Having completed your report make sure that you read it ALOUD and check that it demonstrates these characteristics

- Concise communication of understandings, findings, arguments and conclusions is demonstrated by the use of genre conventions.
- Accurate communication of understandings, findings, arguments and conclusions is demonstrated by the fluent and consistent use of scientific language, representations and conventions.
- Suitable communication of understandings, findings, arguments and conclusions is demonstrated by correct referencing of sources.

Science as a human endeavour

Science as a human endeavour (SHE) features develop foundational skills that support Science inquiry. They provide essential stimulus for the Research investigation, providing a foundation for you to launch into Research investigation internal assessment 3 (IA 3) and build proficiency in Assessment objectives 1, 2, and 3. The SHE features provide practise in writing research questions, planning and conducting experiments, recording information, and reflecting on processes. You will learn to process, analyse, and interpret evidence, evaluate conclusions and claims critically, and communicate your findings effectively.

Syllabus subject matter

Unit 1: Thermal, nuclear and electrical physics

Science as a human endeavour 1: The Drake equation

- Scientific knowledge can enable scientists to offer valid explanations and make reliable predictions

Science as a human endeavour 2: Heating and cooling homes

- Recognise that the science of heating processes is of key importance to the development of efficient and cost-effective technologies that use sustainable and renewable energy sources.

Science as a human endeavour 3: Radioisotopes and radiometric dating

- Consider how an understanding of radioactive decay can enable scientists to make reliable predictions in radiometric dating of materials.

Science as a human endeavour 4: Harnessing radioactive materials

- Explore advances in medical treatment and imaging that have come from a deepening understanding of the properties of nuclear radiation.
- Consider how scientific knowledge can be used to predict beneficial and/or harmful or unintended consequences, e.g. choosing appropriate radioisotopes for medical imaging, carefully storing nuclear waste.
- Consider the health and environmental risks associated with the use of nuclear fission along with the environmental and cost benefits of lowering fossil fuel consumption.

Science as a human endeavour 5: Marie Curie

- Appreciate the significant contributions of scientists such as Marie Curie, Irene Curie-Joliot, Lise Meitner and Otto Hahn who furthered our understanding of radiation and nuclear stability.
- Appreciate that the development of models of the atom often required a wide range of evidence from multiple individuals and across disciplines.

Science as a human endeavour 6: Energy production in stars

- Appreciate that energy production in stars was attributed to gravity until the knowledge of nuclear reactions led to the understanding that energy production in stars is due to nuclear fusion.

Science as a human endeavour 7: Electrical energy in the home

- Appreciate how developing new household electrical devices to improve the efficiency of existing devices and ensure consistency of electrical standards requires international cooperation between scientists, engineers and manufacturers.
- Explore the concerns about sustainable energy usage and global warming that have led to international research and development to improve the energy efficiency of electric lighting.

Science as a human endeavour 8: Why conventional current is 'wrong'

- Appreciate the significant contributions of scientists such as Gustav Kirchhoff, Georg Ohm, Hertha Ayrton and Florence Violet McKenzie who furthered our understanding of electrical currents.
- Appreciate how international conventions enable clear communication of ideas and findings across the globe, e.g. conventional current.

Science as a human endeavour 9: Powering Australia

- Explore the impacts of increased use of household electrical devices during extreme weather, e.g. heat in Australian summers or cold in European winters.
- Appreciate how developing new household electrical devices to improve the efficiency of existing devices and ensure consistency of electrical standards requires international cooperation between scientists, engineers and manufacturers.
- Consider the impacts of computers, smartphones and the internet on society and their reliance on a stable supply of electricity.

Unit 2: Linear motion and waves

Science as a human endeavour 10: Isaac Newton

- Appreciate the significant contributions of scientists such as Isaac Newton and Émilie du Châtelet.
- Appreciate that the laws of motion proposed by Isaac Newton provided an explanation for a range of previously unexplained physical phenomena, which were confirmed by multiple experiments performed by a multitude of scientists.

Science as a human endeavour 11: Road safety and technology

- Consider how knowledge of forces and motion has led to improvements in car safety through the development of technologies such as seatbelts, crumple zones and airbags.

Science as a human endeavour 12: Monitoring earthquakes and tsunamis

- Appreciate that knowledge of different types of waves, and their motion through the ocean and the continents, allows prediction of the possible extent of damage or the timing of a tsunami.

Science as a human endeavour 13: Noise pollution and acoustic design

- Consider how acoustical engineering can reduce noise pollution by planning structures that absorb sound waves or that do not reflect and amplify sound in an unwanted way.

Science as a human endeavour 14: Development of the wave theory of light

- Appreciate the significant contributions of scientists such as Laura Bassi, Willebrord Snellius, Albert A Michelson and Edward W Morley.
- Appreciate the role of experiments in furthering our understanding of light and its wave-like behaviour.
- Consider the importance of wave properties in experiments such as those performed by Michelson and Morley to demonstrate light waves travel through a vacuum and not the luminiferous aether as was believed at the time.

The Drake equation

Physics problems usually include enough information to calculate a precise and correct answer. When insufficient information is given the answer must be estimated. To estimate a calculation, you can use orders of magnitude. Problems that ask for an estimate are called Fermi questions, after the Italian physicist Enrico Fermi, who worked in nuclear physics in the 1930s.

Fermi questions use approximations and orders of magnitude. An order of magnitude is the power of 10 that the quantity is closest to, rounded up if the coefficient is 5 or above. Orders of magnitude are a comparison of the size of quantities; they do not represent exact values. For example, the universe is generally accepted to be 13.8 billion years old, or 4.35×10^{15} s. So, the order of magnitude of the age of the universe in seconds is 15.

One of the most famous Fermi questions is: What is *N*, the number of intelligent alien civilisations in our galaxy? This can be estimated by using orders of magnitudes in the Drake equation, as shown in Figure 12.1.1. Frank Drake, an astronomer from the USA, first conceived this in 1961.

The factors contained in the Drake equation relate to variables that change the probability that an intelligent civilisation will arise on a given planet, as shown in Table 12.1.1.

All scientists know is that the answer is at least 1, and could be anywhere from 1 to millions.

FIGURE 12.1.1 The Drake equation gives an estimate of how many intelligent and communicative alien civilisations are in our galaxy.

TABLE 12.1.1 The factors used in the Drake equation to estimate the number of communicative, intelligent, alien civilisations in our galaxy

Factor	Description	Min value	Max value	Notes
R^*	rate of star formation in the Milky Way galaxy at number of new stars per year	1.5	3	This is the most accurately known value of all factors.
f_p	the fraction of those stars that have planets orbiting	0.2	1	The thousands of exoplanets discovered in the last 10 years is evidence that this factor is very close to 1.
n_e	the number of those planets, per star, that can support life	0.1	5	This value is becoming more accurately known from the number of Earth-like planets found as exoplanets each year.
f_L	the fraction of those planets on which life arises	10^{-4}	1	This factor is difficult to determine because you only have one data point and that is Earth.
f_i	the fraction of those planets on which intelligent life or civilisation develops	10^{-9}	1	This is the most unknown factor.
f_c	the fraction of those planets that develop technology that transmits proof of their existence into space	0.2	1	It is generally thought that once intelligent life arises, it will quickly develop advanced technologies.
L	the length of time, in years, that the civilisation releases information into space about its existence	300	10^9	This value can be estimated from a survey of all known civilisations that have existed, and still exist, on Earth.

KEY QUESTIONS

Forming and finding

1 Distinguish between an estimate and an order of magnitude.

2 Explain why the Drake equation only gives an estimate for *N*.

3 Using the minimum and maximum values for the factors in the Drake equation, determine a lower and upper estimate for *N*.

4 Locate an up-to-date source which states how many exoplanets have been discovered. Evaluate the reliability of the selected source.

Analysing

5 The first exoplanet, or planet orbiting another star, was discovered in 1995. Explain how this resolved a significant limitation in the Drake equation.

6 The value for *L* is based on Earth's data. Identify two limitations with this approach.

Heating and cooling homes

As the population grows and homes get bigger, more energy is consumed. A 2022 report by the Queensland government showed there was an increase of approximately 20% in maximum energy demand between 2013 and 2022, with an expected 30% increase or more by 2032. Around 40% of energy used in the home is used in active heating and cooling via appliances, such as air conditioning and space heaters.

Rising energy costs, dwindling resources and environmental concerns are driving a decrease in fossil fuel use. It is increasingly common to see solar panels on the roofs of homes. Australia is at the forefront of exciting research into solar cells, including new flexible-solar-cell technology, and is exploring the large-scale use of solar power with, for example, the Sunshine Coast Solar Farm. Understanding thermal processes allows architects to develop simple and effective ways to heat and cool buildings without electricity.

Passive solar heating is one way to reduce energy consumption. Buildings that are designed with passive solar heating and cooling in mind take advantage of natural climate to maintain a comfortable temperature indoors. Figure 12.2.1 describes some of the principles of a passive solar house.

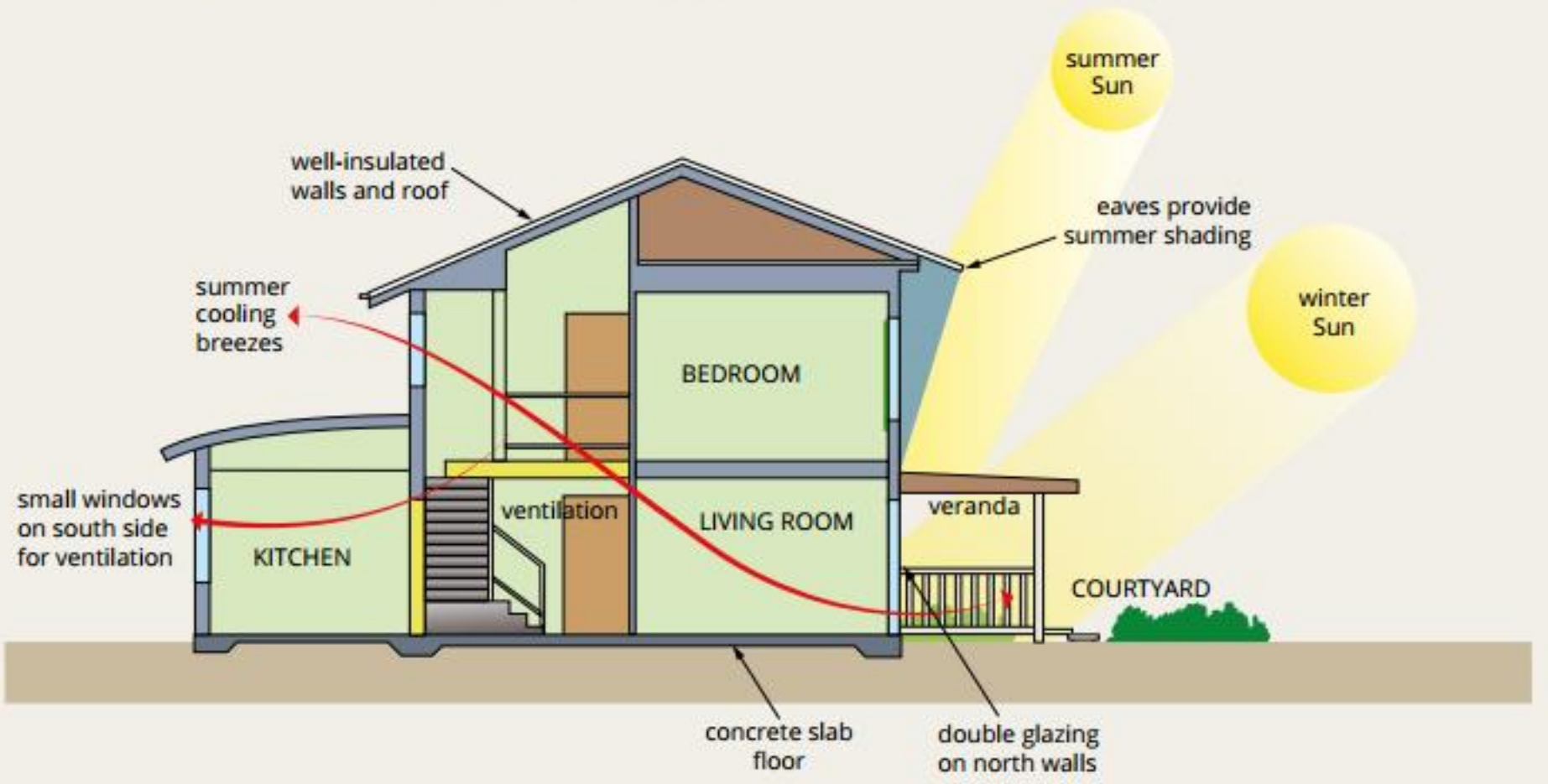


FIGURE 12.2.1 Aspects of good passive solar design applied to housing design can lead to significant energy savings.

Solid brick walls and concrete slab floors provide large amounts of thermal mass, which take longer to heat up on hot days and to cool down on cold nights. Large windows on the northern, sunny side of a house allow solar energy to warm the interior, while small windows on the southern, shady side provide ventilation and reduce heat loss. Living areas positioned on the northern side allow the winter sun to warm high-use areas of the house. Rooms that are not used during the day, such as bedrooms, can be on the southern side of the house.

Double glazing (Figure 12.2.2) can reduce conductive heat loss at night and in winter, and reduce solar energy gains in summer. Conventional single glazing loses heat through conduction. Double glazing provides additional thermal resistance by adding a sealed space between two glass panes. The air gap conducts much less heat. Increasingly, argon gas is used to fill the space between the panes instead of air, because it has a lower conductivity than air. Double glazing can be further improved with 'thermally broken' aluminium frames. These frames include a rubber strip around the frame to further prevent conduction. Good use of double glazing can reduce heat loss or gain by more than 50%.

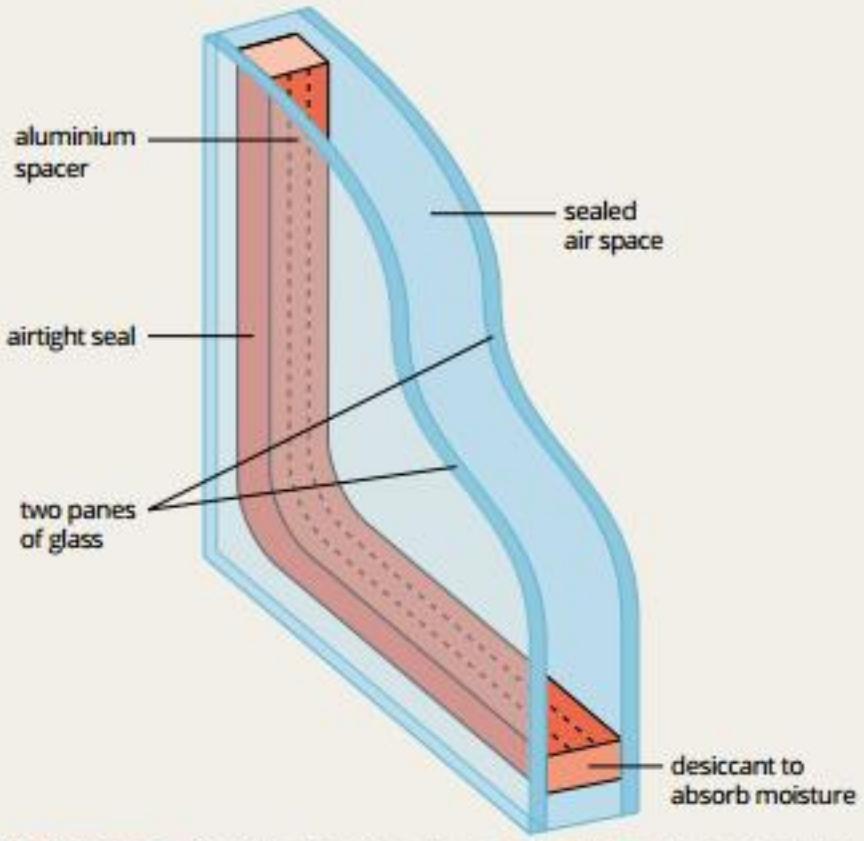


FIGURE 12.2.2 Double-glazed window construction reduces heat loss through windows that would otherwise transfer considerable energy through conduction.

Insulation can further improve energy savings in building design. Insulation primarily limits conductive and convective heat transfer. This is typically achieved by creating small pockets of air within a material which is a poor conductor, such as fiberglass or foam. Insulation is usually installed during construction, such as in Figure 12.2.3 where fiberglass 'batts' are being installed in a roof cavity, but it is also possible to retrofit insulation after construction. The resistance to heat flow provided by an insulator is measured by the materials 'R-value', the higher the value, the better the insulator.

FIGURE 12.2.3 Pink fiberglass 'batts' are a common form of building insulation. Placing these batts in the ceiling limits heat loss from the interior of the home, which is important due to warm air rising in convection.

While some traditional forms of insulation can be sustainable, such as recycled glass wool, others require large amounts of plastic and produce harmful greenhouse gasses during manufacture. To combat this, nanotechnologies are being investigated for use in building and construction, such as polymer reinforced aerogels developed by NASA (see Figure 12.2.4). Aerogels are sponge-like materials filled with nanometre sized pockets of air. Aerogels are very effective insulators as they are 95% air. Another promising nanotechnology is hollow glass microspheres which can be incorporated into materials and coatings directly to improve their insulative ability.

FIGURE 12.2.4 Aerogels are surprisingly strong despite their incredibly low density. The large amount of air contained within the aerogel's structure makes it a very effective insulator.

KEY QUESTIONS

Forming and finding

1. Contrast active and passive heating and cooling methods.
2. Identify the properties of an insulative material.
3. List the heat transfers that insulation reduces.
4. Select a form of insulation and find a credible source which states the R-value of the insulation. Evaluate the reliability of the selected source.

Analysing

5. A group of scientists are investigating the performance of insulative materials. Half of the group research insulators in the arctic, and the other half research insulators in regional Queensland. How would combining their research impact the validity of their conclusions?
6. The text claims that higher R-values are better insulators. Create a research question using this claim as a starting point.

Radioisotopes and radiometric dating

Carbon dating

Carbon dating is used by archaeologists to determine the ages of fossils and other ancient objects made from organic matter. It involves measuring and comparing the proportions in the object of two isotopes of carbon, ^{12}C and ^{14}C.

Carbon-12 is a stable isotope. Its atoms are about 1 000 000 000 000 (10^{12}) times more common than carbon-14 atoms.

Carbon-14 is radioactive. It only exists in small amounts in nature. It has a half-life of 5730 years and decays by beta negative emission to nitrogen-14. Its decay equation is:

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta + ^{0}_{0}\overline{\nu}$$

Both carbon-12 and carbon-14 can combine with other atoms in the environment. For example, they both combine with oxygen to form carbon dioxide. Plants and animals take in carbon-based molecules from the air and food. This means that all living organisms contain the same percentage of carbon-14. In the environment, the production of carbon-14 is matched by its decay and so the proportion of carbon-14 atoms to carbon-12 remains constant in living organisms.

After an organism dies, the amount of carbon-14 it contains will decrease, because these atoms decay to form nitrogen-14. They are not replaced from the environment because the organism no longer needs nourishment. The number of atoms of carbon-12 does not change because carbon-12 is a stable atom. So, over time, the proportion of carbon-14 to carbon-12 atoms decreases. The proportion of carbon-14 to carbon-12 in a dead organism can be compared with the proportion found in living organisms and the approximate age of the specimen can be determined from the half-life of carbon-14.

In 1988, scientists used carbon-dating techniques to show that the Shroud of Turin was probably a medieval forgery. It had been claimed that Shroud of Turin was the piece of cloth that was the burial shroud of Jesus Christ (Figure 12.3.1). Carbon-dating tests on small samples of the cloth established that there was a high probability that it was made between 1260 and 1390, not around the time of Christ's death.

FIGURE 12.3.1 The Shroud of Turin

Radiocarbon dating is an important aid to anthropologists who are interested in finding out about the migration patterns of early people, including Indigenous Australians. This powerful technique can be applied to the remains of ancient campfires. It is accurate and reliable for samples up to about 60 000 years old.

Carbon dating cannot, however, be used to date dinosaur bones as they are more than 60 million years old. But it can be used to determine the age of more recently extinct animals from their fossils, such as the extinct Australian marsupial *Diprotodon* shown in Figure 12.3.2.

FIGURE 12.3.2 The skull of a *Diprotodon* found in 1979 in northern New South Wales. Charcoal found buried near the skull was carbon-dated to be about 33 500 years old, giving an indication of when this animal lived.

Radioactive decay series dating of rocks

Radiometric dating is use to determine the age of a rock sample. It involves comparing the amount of uranium-235 to the amount of lead-207 in zircon crystals (zirconium silicate, $ZrSiO_4$) contained in the rock sample. The uranium-235 nuclei decay via a series to the stable isotope lead-207, with a half-life of 710 million years. It is assumed that all the uranium, and none of the lead, found in the zircon crystals was present at the time the rock sample was formed, and that all the lead was created because of the decay series of uranium-235. The oldest piece of Earth's crust is shown in Figure 12.3.3.

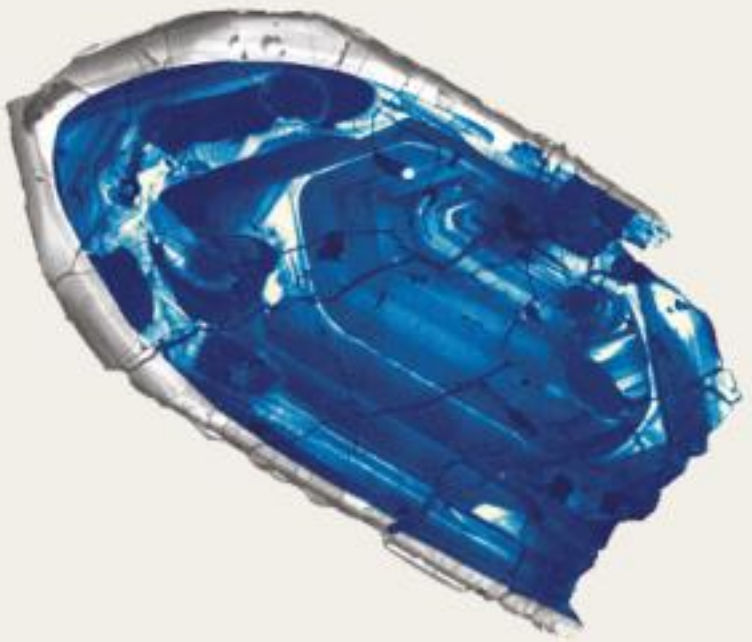


FIGURE 12.3.3 The oldest piece of the Earth's crust is this blue crystal of zircon found in mid-Western Australia.

KEY QUESTIONS

Forming and finding

1. Explain why carbon dating cannot be used to determine the age of metal-based archaeological artefacts.
2. Explain why measurements of the isotope lead-207 are important in this method of dating rocks.
3. The oldest piece of the Earth's crust was found in the Jack Hills region of mid-Western Australia. In a zircon crystal (Figure 12.3.3) in a rock sample taken from this region, the ratio of the number of lead-207 nuclei to the remaining uranium-235 nuclei is 62.98. Use this number to determine the age of the rock sample.
4. Carbon dating does not work for specimens older than 60 million years, or for specimens that do not contain carbon. Locate a source for a radiometric dating method which does not utilise carbon. Evaluate the reliability of the selected source.

Analysing

5. Starting in 1945, multiple nuclear detonations occurred around the world which significantly increased the amount of carbon-14 in the atmosphere. Evaluate the limitations this may pose for carbon dating.
6. Scientists can analyse small samples taken from famous artworks to determine if they are authentic pieces, or modern forgeries. Describe the implications carbon dating would have for this practical application.

Harnessing radioactive materials

Nuclear power

More than thirty countries use nuclear power. This makes up approximately 10% of global power generation across approximately 400 reactors. France leads the world in nuclear power generation – around 60% of its electricity is produced by nuclear fission reactors.

Fossil fuels dominate Australia's energy production and contribute to global warming via the production of greenhouse gas. Nuclear fission, however, produces almost no carbon dioxide. Fission is also more efficient than burning fossil fuels: 1 kg of uranium-235 fuel in a reactor produces millions of times more energy than the same mass of fossil fuel. Uranium hexafluoride, a typical fuel in fission reactors, has high energy density — each small pellet can produce 480 GJ of energy.

Fission reactions produce many isotopes and some of these are very radioactive and have long half-lives. There is a continuing debate as to what to do with this waste – should it be dumped in the ocean, buried, or launched into the Sun?

Countries that use fission require uranium as a fuel, which they may have to import from another country. This creates security issues with transportation: a third party might intercept shipments and modify the fuel to produce nuclear weapons.

Nuclear fission is generally safe, but when accidents occur, the consequences are disastrous. There have been three major nuclear reactor incidents (USA in 1979, Ukraine in 1986, and Japan in 2011). Each time, the reactor's cooling systems failed, the nuclear fuel melted into the floor (Figure 12.4.1), the fission reactions became uncontrolled, and explosions released radioactive material into the environment.

FIGURE 12.4.1 Solidified radioactive 'lava' made of concrete

Nuclear medicine

Around 30 countries use nuclear reactors for power, but more than 50 use them to develop radiopharmaceuticals (medical isotopes for diagnostic imaging and treatment). The nuclear reactor in Lucas Heights, Sydney, is an example.

Fluorodeoxyglucose (FDG) is a radiopharmaceutical used for diagnostic imaging. FDG is a molecule of glucose, a type of sugar, where part of the sugar molecule has been replaced with an atom of radioactive fluorine, F-18. Once inside the body, FDG accumulates in areas of high metabolic activity such as the brain or rapidly growing tumours (Figure 12.4.2). They show function inside the body, rather than just structure.

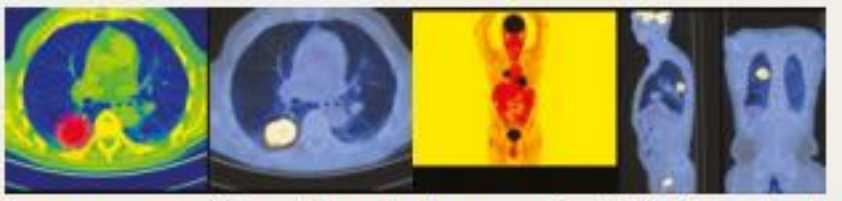


FIGURE 12.4.2 Diagnostic radiopharmaceuticals differ from structural scans such as X-rays because they show areas of increased activity, as opposed to structural detail.

Radium-223 is a 'bone-seeking' radiopharmaceutical used to treat cancer. Radium is an alkaline earth metal; it is absorbed by bones with minimal interaction with other parts of the body. This allows for targeted treatment of bone cancers without harming other areas of the body. These 'bone-seeking' isotopes reduce damage inflicted by treatment technologies such as external beam radiation therapy where all parts of the body in the path of the beam are irradiated.

KEY QUESTIONS

Forming and finding

1 Explain how energy density affects power generation.
2 Identify the benefits and risks associated with the use of fission power.
3 Contrast a structural image and a functional image in diagnostic medicine.
4 Distinguish between a controlled and an uncontrolled fission process.

Analysing

5 The article presents the claim that radiopharmaceuticals can be used both for diagnostic imaging and for treatment. Create a research question from this claim.
6 What implications do targeted radiopharmaceuticals have for the health outcomes of cancer patients?

Marie Curie

Marie Curie is one of only five scientists to receive two Nobel prizes, and the only scientist to receive a prize in more than one discipline.

Marie Curie's thesis '*Recherches sur les substances radioactives*' details investigations into radiation. The study of 'rays' was a new area of research thanks to Wilhelm Röntgen's discovery of X-ray radiation. Shortly after, Henri Becquerel discovered penetrating radiation which emanated from a sample of uranium ore. Becquerel demonstrated that this radiation caused a gas to become conductive. The emission from uranium appeared spontaneous. Many in the scientific community turned their attention to uncovering the source of this energy.

Marie Curie was one such scientist. She, along with her husband Pierre, constructed a piezoelectric electrometer (Figure 12.5.1) to apply a potential difference to the mineral within a circuit. The current in the circuit would be proportional to the radioactivity of the mineral. To accurately measure this current, a known quantity of current was applied in the reverse direction until the current cancelled to zero. Curie believed radiation was an atomic property, stating it would be irrational for this property to apply exclusively to uranium. She tested several minerals to investigate this claim, a sample of which can be seen in Table 12.5.1.

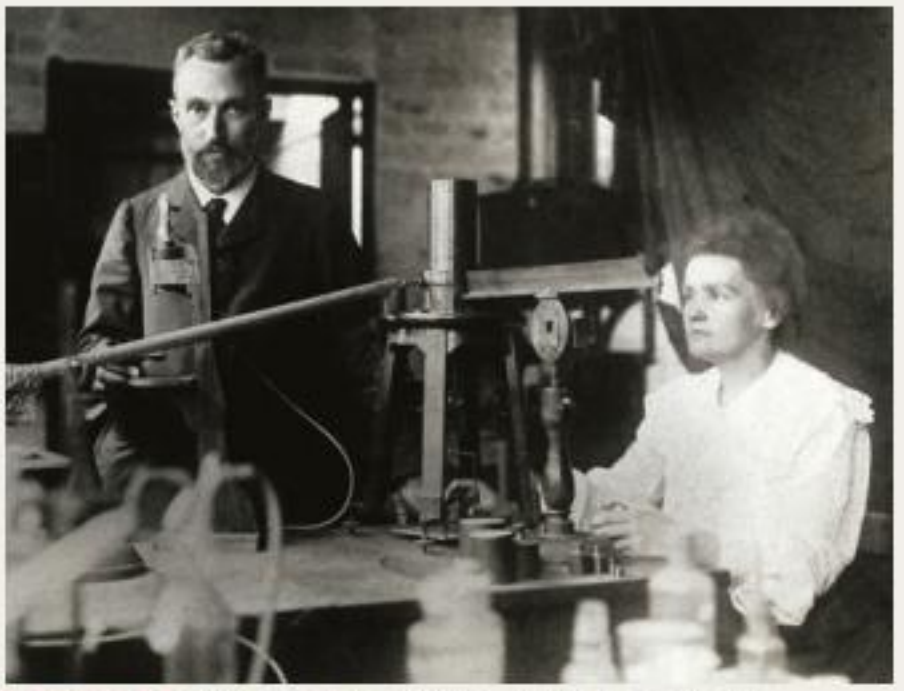


FIGURE 12.5.1 Marie and Pierre Curie, with their piezoelectric electrometer

TABLE 12.5.1 A sample of the data obtained by Curie in the electrometer experiments

Mineral	Current ($\times 10^{-11}$ A)	Mineral	Current ($\times 10^{-11}$ A)
uranium	2.3	autunite	2.7
pitchblende	8.3	orangite	2.0
cleveite	1.4	monazite	0.5
chalcolite	5.2	carnotite	6.2

These results indicated the existence of elements with greater radioactivity than uranium. Curie named these elements radium and polonium and spent several years working to isolate them from a ton of pitchblende ore. At the end of this process, she was left with approximately 0.1 grams of radium chloride salt – just enough to identify the atomic mass and spectrum of radium—confirming its existence as a new element.

Curie demonstrated that the ionising ability of these new elements was 10^6 times greater than that of radium. Using Ernest Rutherford's classification of rays as alpha (α), beta (β) or gamma (γ), Curie investigated the properties of the rays released from radium and polonium by measuring their penetrative ability and deflection within a magnetic field.

KEY QUESTIONS

Forming and finding

1 Explain why uranium being a source of spontaneous energy was confronting to scientists.

2 State the claim Curie made which her initial research was intended to investigate.

3 Explain how the measurement of current was related to the radioactivity of a substance.

4 Use a scientifically credible source to assist you to describe induced radioactivity. Reference the source appropriately at the end of your description.

Analysing

5 Compare the results for pitchblende, chalcolite, atunite, and carnotite with the result for uranium, including the significant insight this provided to Curie.

6 Explain how spectral analysis and atomic weight measurement were key in confirming radium as a new element.

SCIENCE AS A HUMAN ENDEAVOUR 6

Energy production in stars

Lord Kelvin (William Thomson) was one of the key figures in early attempts to explain the mechanism behind heat and light from the Sun. Kelvin initially proposed that the Sun was a hot glowing (incandescent) ball, cooling over time. Subsequent calculations revealed this theory to be insufficient to explain the quantity of heat and light released by the Sun.

Julius Mayer was the first to propose the meteoric theory, which involved the kinetic energy of meteors and other objects being transferred into heat as they collided with the Sun. This theory was eventually rejected as the increase in the Sun's mass would decrease the length of Earth's year which measurements were able to disprove (not to mention the astonishing number of meteors required to support the observed brightness of the Sun).

Hermann von Helmholtz was the first to propose gravitational collapse as the source of the Sun's energy. He supposed that the Sun was initially a cloud of dust which had collapsed inwards over time releasing gravitational potential energy as heat and light.

Kelvin considered all these factors as part of what became known as the Kelvin-Helmholtz theory where it was believed meteoric collisions and gravitational collapse were both responsible. This theory suggested the Sun decreasing in size by one-tenth of a percent in diameter released enough energy for 20 000 years. While gravitational collapse is indeed part of the story of the formation of our solar system, calculations using this theory contradicted with known values for the age of Earth (and, therefore, the Sun). Despite this, Kelvin remained steadfast in his belief that his calculations were correct and claimed that either the age of the Earth provided by geological and evolutionary theories was wrong, or that as-yet undiscovered laws of physics would provide the correct explanation.

Kelvin was correct – his theory was proven wrong. Marie Curie's discovery of radium and polonium drew sufficient attention to radiation that scientists started to investigate it as a source of the Sun's energy. Ernest Rutherford incorrectly suggested that the radioactive decay of a substance such as radium could be responsible for the Sun's output. However, the only evidence found to support this theory was the discovery of Helium on the Sun, which could be from the release of alpha particles released as part of a radioactive decay.

Arthur Eddington posited that fusion of hydrogen into helium was responsible for the energy output of the Sun. Francis Aston discovered that the mass of a helium atom was slightly less than the mass of the four hydrogen atoms. This fact, coupled with Einstein's mass–energy relationship $E = mc^2$, provided Eddington with the reasoning required to justify the fusion of hydrogen as the source. Cecilia Payne (Figure 12.6.1a) in her doctoral thesis calculated the proportions of hydrogen and helium within the Sun as approximately 74% and 24% respectively, which was later confirmed using spectroscopy (Figure 12.6.1b). This provided significant evidence for the fusion hypothesis and allowed the nuclear equations for stellar fusion to be developed by Hans Bethe.

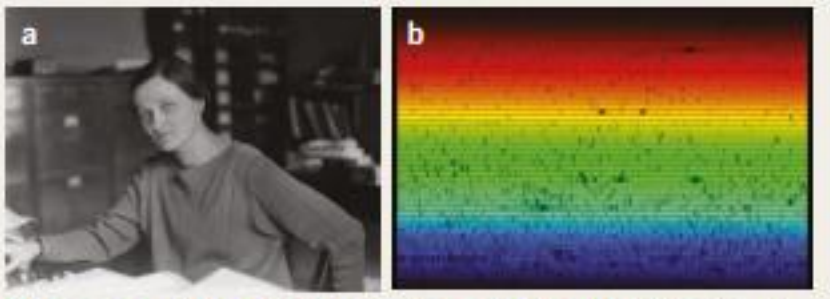


FIGURE 12.6.1 (a) Cecilia Payne was a notable astrophysicist and the first female professor and department head at Harvard University. Astrophysicist Otto Struve referred to her thesis as the most brilliant Ph.D. thesis ever written in astronomy. (b) Solar absorption spectrums were used to verify the chemical composition of the Sun. The dark lines correspond to wavelengths absorbed by particular elements.

KEY QUESTIONS

Forming and finding

1. James Prescott Joule's work showing the conversion of kinetic energy into heat paved the way for many of the theories discussed in this article. Select one theory from the article and explain how it is affected by conservation of energy.
2. Distinguish between Rutherford and Eddington's theories.
3. Summarise the historical understanding of energy production in stars using a flow chart.
4. The article does not detail the immense temperature and pressure within the Sun required for stellar fusion to take place. Locate a scientifically credible source which extends your knowledge on how these conditions allow fusion to take place.

Analysing

5. How did data analysis contribute to the rejection of meteoric theory?
6. What scientific insights were gained by incorporating understanding from different fields of science to explain energy production in stars?

Electrical energy in the home

A 2023 report from the Australian Bureau of Statistics showed household electricity use has decreased by 4%. But scientists are still working to improve energy efficiency.

Lighting accounts for around 10% of energy use in the home. Traditional incandescent light bulbs (Figure 12.7.1a) are inefficient; more than 95% of their energy is wasted as heat. Compact fluorescent lamps (CFLs) and light-emitting diodes (LED) are more efficient, using around 20% of the energy of incandescent bulbs.

FIGURE 12.7.1 (a) An incandescent bulb, (b) a CFL bulb, (c) an LED bulb and (d) an OLED

Organic light-emitting diodes (OLEDs) contain an organic compound (such as carbon) and emit light when an electric current is applied. They are usually made into larger flat surfaces. OLEDs are used in some mobile phone screens, TVs and laptops. OLED screens are thinner than LED screens. They can be used as a coating on windows that are transparent in the daytime and light up at night, or on flexible surfaces.

A team at the University of Queensland, led by Dr Ebinazar Namdas, is working with scientists in India to develop the organic semiconductor technology used in OLEDs. They aim to reduce cost, improve efficiency and provide energy-efficient lighting for remote communities.

You can also save energy by changing how and when you use devices. Older analogue household energy meters (see Figure 12.7.2a) required a technician to travel to the residence to read. Modern smart meters (see Figure 12.7.2b) are internet connected and can report electricity usage every five minutes to the company and the resident's account, allowing them to track and adjust their usage accordingly.

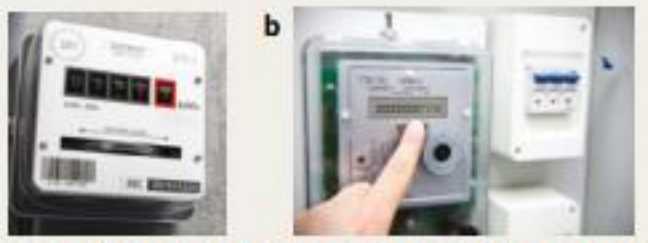


FIGURE 12.7.2 (a) An old analogue meter and (b) a smart meter

Smart devices can also improve household energy efficiency. Smart lighting can be programmed to turn off automatically when nobody is in a room. Smart refrigerators can detect if they have been left open, or use built in cameras to show their contents and to reduce how often they are opened. Smart power strips and plugs can detect when the main device (such as a television) is turned off and cut power to other devices connected to the same board (such as speakers). Internet connectivity allows consumers control of when these devices are used. For example, a resident could activate their dishwasher via a smartphone app when not at home so they make use of solar power during sunny weather, saving both money and emissions.

KEY QUESTIONS

Forming and finding

1 Describe what is meant by the term 'smart' in relation to modern devices.

2 Identify the advantages of OLEDs over LEDs.

3 Identify one of the research claims associated with Dr Ebinazar Namdas' work.

4 Manufacturers frequently claim increased efficiency and savings from their smart devices. Evaluate the credibility and reliability of this type of source.

Analysing

5 This article claims that technological advancement has decreased household electricity use. Can you propose alternate explanations?

6 List two limitations to consider when comparing energy efficiency of different lighting technologies.

Why conventional current is 'wrong'

In the late 18th century Luigi Galvani made a frog's leg contract by connecting the nerves with metallic instruments. He called this phenomenon 'animal electricity' and believed this electromotive force came from inside the animal. Alessandro Volta disagreed, showing that two different metals connected by a salt-based medium (such as a frog leg) could produce an electromotive force on their own. This debate led to the development of the first reliable source of electricity, a form of early battery. This type of battery (see Figure 12.8.1) is called the Galvanic Cell by some and the Voltaic Cell by others, showing that in some sense, their debate continues over 200 years later.

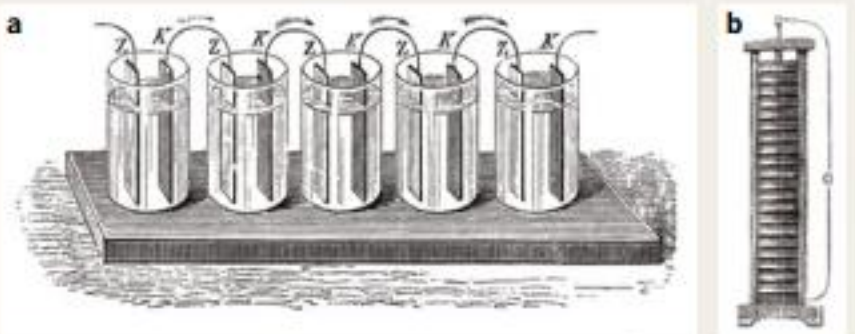


FIGURE 12.8.1 (a) Early cells were two strips of differing metals submerged in a salt solution. (b) Volta refined this design considerably, storing discs of metal with salt-soaked fabric between them in a device known as the voltaic pile.

Hans Christian Oersted was demonstrating the operation of one of these cells when he noticed a nearby compass was deflected by a field originating within the wires. His investigation of the field generated by current carrying wires gave birth to the field of 'electromagnetism'.

André-Marie Ampère undertook the mathematical work of explaining Oersted's observations. As part of his mathematical derivations, Ampère concluded there must be a single loop of electromotive force causing 'molecules of current' to travel through the circuit. Ampère successfully demonstrated the repulsion and attraction between parallel wires by manipulating their direction. This new physical quantity was called current, which Ampère showed must be proportional to the number of molecules passing through a wire each second.

FIGURE 12.8.2 Oersted's demonstration of the deflection of a magnet by a current carrying wire. Note the two metal rods submerged in a glass on the table – this is the cell powering his circuit.

Gregor Ohm took this work a step further and used the magnitude of compass deflection to investigate the strength of the variables. He connected various thicknesses and lengths of wire to a voltaic cell and noted the corresponding amount of deflection. This allowed him to define the relationship which became known as Ohm's law. The amount of resistance given by a particular length and thickness of wire was directly proportional to the electromotive force supplied via Volta's source of potential and was indirectly proportional to the amount of Ampère's current.

Like Ampère and Oersted, Gustav Kirchhoff took the mathematical work of Ohm a step further. A 21-year-old student of mathematics and physics, Kirchoff published a paper which later in his career became his doctoral thesis. This paper detailed the laws of conservation of electrical charge and voltage, which are frequently referred to as Kirchhoff's laws. His work on these laws secured a scholarship and began his rapid rise to adjunct professor, then full professor status.

It should be noted that all the discoveries detailed above were made prior to J.J. Thompson's discovery of the electron. Indeed, Kirchhoff ignored the cause of current and deliberately focused on mathematically explaining how it behaved. At the time, there were two prevailing theories. Oersted believed the two ends of a battery were in 'electric conflict' with each other with the positive end creating an electromotive force in one direction and the negative end creating a force in the other direction.

Ampère's work instead focused on 'electric current', because a definite direction of flow was required to explain the observed electromagnetic effects. These two conflicting ideas gave rise to the definition of having 'conventional current' flow in a direction from the positive terminal to the negative terminal. It was realised shortly after J.J. Thompson's discovery, that electrons were responsible for current, and they flowed in the opposite direction to what was already established. Alas, the ship had already set sail. It is for this reason we refer to conventional current and electron current as separate but intrinsically related ideas.

KEY QUESTIONS

Forming and finding

1 Around this time, the field of mathematical physics was becoming popular, with mathematical work replacing experimentation for some scientists. The work of Ampère is one such example. Identify the type of proportionality Ampère mathematically demonstrated existed for electrical current.

2 Distinguish between the proportionality of resistance with voltage, and resistance with current.

3 Contrast conventional current with electron current.

4 Prior to the invention of the voltaic/galvanic cell, a device called a Leyden jar was used. Use a scientifically credible source to research the Leyden jar. Contrast the Leyden jar with the voltaic/galvanic cell.

Analysing

5 Oersted incorrectly claimed there was a force pushing from the positive end of a battery, and another force pushing from the negative end of the battery. If this were true, what would happen to electricity in the exact middle of the circuit?

6 In his work on resistance, Ohm initially investigated the effect of length and thickness of wire. Redirect Ohm's experiment by suggesting another variable which could be investigated.

Powering Australia

Australia's power distribution network has always been complex requiring innovation and cooperation between scientists, engineers and manufacturers. Outside the major cities, the population density is low and distances between communities are large. Power transmission over long distances leads to energy losses, problems managing and maintaining the infrastructure, and the risk of bushfire.

Australia also faces the challenge of changing energy production from centralised coal- and gas-fired power stations to a model that includes large-scale renewables together with energy generated in the home by solar panels, to reduce carbon emissions and cut energy costs. The Queensland Government's Energy and Jobs plan has committed to 70% renewable energy by 2032, and 80% by 2035. Currently, just over 10% of this is provided by rooftop solar.

In the past 20 years, rooftop solar panels (Figure 12.9.1) have moved from new technology to a common sight on Australian homes. Queensland is the national leader in rooftop solar with panels which are now installed on more than a third of Queensland homes, generating around 5000 MW. However, the large-scale adoption of solar panels is hampered by problems connecting to the electricity grid, which was designed to deliver power to homes, and not the other way around.

FIGURE 12.9.1 Rooftop solar panels on an Australian home

Analysis of daily power demand data, such as Figure 12.9.2, reveals one of the challenges Queensland's electricity grid faces with increased solar uptake. Prior to rooftop solar, electricity demand was at its lowest overnight while people were asleep. Solar has caused this minimum to occur around midday. Additionally, as more homes install solar, the minimum demand in the middle of the day is decreasing year-to-year. This poses significant complexities for the grid as Queensland transitions to a greater mix of renewable sources.

Power generation falls generally into two categories – baseload sources and variable sources. Baseload sources are incapable of quickly responding to changing demand and need to remain operating constantly at a steady state. Coal and nuclear are common examples which can take many days to start/stop. Variable sources include natural gas and hydroelectric which can respond much more rapidly to changes in demand. Times when demand drops below currently active baseload poses a complex challenge for the electricity grid.

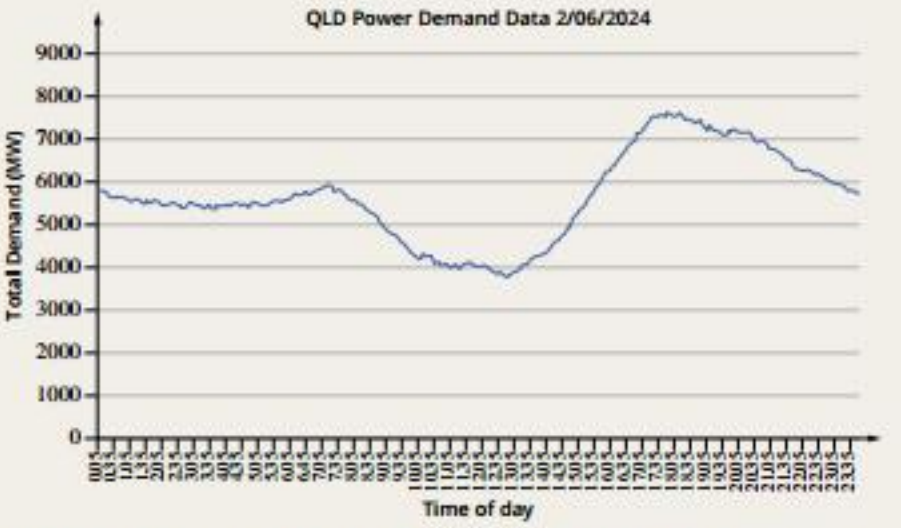


FIGURE 12.9.2 Australian Energy Market Operator (AEMO) aggregate demand data for Queensland on the 02/06/2024. The AEMO refers to demand graphs of this shape as 'Duck Curves' as they apparently resemble the shape of a duck. The decrease in electricity demand during the middle of the day when solar energy is abundant can be clearly seen in the data.

One way around this is to use batteries to store extra power for later use, particularly in the evenings when electricity use is at its highest and when solar panels do not generate electricity. As battery technology improves, these will become available and affordable to have at home. The CSIRO estimates that 'By 2050, over 10 million customers will own distributed resources like solar, storage, home energy management systems and electric vehicles, which they can use to sell grid support services worth $2.5 billion per year'.

Large-scale renewable-energy projects are also being developed. But what happens when the sun does not shine or the wind does not blow, and energy is still needed? The large-scale adoption of renewable energy has been held back by these concerns and by limitations in battery technology. But battery storage has improved dramatically. The Woolooga solar farm in Gympie generated 438 000 MWh of power in 2023 and is in the process of building a 400 MWh battery onsite which would store enough power to support 26 000 homes.

Tesla has already built a 100 MW battery, the largest lithium-ion battery in the world, to store energy from a new wind farm in South Australia (Figure 12.9.3). Storage technologies will stabilise the network by storing excess energy during periods of decreased demand which can then be used during periods of shortfall. This provides stability to the grid, energy security to Queenslanders and is an important technology in the transition to a greater mix of renewables.

FIGURE 12.9.3 South Australia's gigantic Tesla lithium ion battery is the world's largest and most powerful. It can dispatch power to 30 000 homes for just over an hour. The battery began dispatching stored wind power to the electricity grid in November 2017.

KEY QUESTIONS

Forming and finding

1 Identify three difficulties that Australia faces with energy provision.

2 Distinguish between baseload sources and variable sources.

3 Explain how storage technologies are affecting the transition to renewable energy sources.

Questions 4 to 6 refer to the data from Figure 12.9.2.

4 The graphed data is aggregate data. Determine if this is a primary or a secondary source of information.

Analysing

5 The data was taken from a sunny winter's day over the weekend. What limitations may be present in this data?

6 What further insights may be gained by extending this analysis over a greater period of time?

Isaac Newton

Isaac Newton (Figure 12.10.1) was born dangerously prematurely on Christmas day, 1642. Newton's father, an illiterate farmer, had died three months earlier. His mother remarried, and left Newton behind with his grandparents. Nine years later, his stepfather died as well. Clearly, the odds were stacked against Newton from the beginning. Nevertheless, Newton became one of the most influential figures in the scientific revolution, if not all of human history.

FIGURE 12.10.1 Isaac Newton

Despite how Newton felt about it (he viewed it as an abandonment and believed it to be the source of his insecurities and anxieties) being left with his grandparents was a great blessing. Unlike his father, his grandmother was literate and began Newton's early education prior to his being sent to boarding school. With his stepfather's death, Newton's mother pulled him from school to manage their farm, which he hated. Fortunately, the headmaster persuaded Newton's mother to allow him to finish his schooling and attend university at Trinity College, Cambridge. Newton took his education quite seriously, independently reading well beyond the standard curriculum, and teaching himself philosophy and mathematics, in addition to his core studies.

Between 1665 and 1667 university was closed due to the plague and Newton was forced to continue his studies back on the farm. During this period, Newton developed Calculus (a new branch of mathematics), discovered white light could be diffracted into colours (Figure 12.10.2), began work on the first reflective telescope, and developed the mathematics behind the laws of motion. These discoveries were the beginning of his masterpiece *Principia* which forms the basis of the domain of Physics known as Classical Mechanics (sometimes referred to as Newtonian Mechanics).

FIGURE 12.10.2 Isaac Newton dispersing white light through a prism

Clearly, isolation was productive for Newton. Indeed, Newton struggled with aspects of public life, becoming involved in several colourful disputes around scrutiny of his work. He was frequently ill-tempered, exasperated and suffered a nervous breakdown. Some (including Newton) believe this behaviour to stem from his childhood. Others believe it to be related to Newton's interest in alchemy which exposed him to substances such as lead, arsenic, and mercury. A posthumous sample of his hair was found to have 40 times higher levels of mercury than expected – not surprising, given his notes described it tasted 'strong, sourish and ungrateful'.

The brilliance of Newton's Principia is in its mathematics. Many of the experiments around the discovery of these concepts were conducted by others. Inertia, for example, was initially deduced by Galileo from the results of his experiments with inclined planes – but it was Newton that was able to formulate the mathematics behind how inertia worked. Newton did later verify his mathematics with several pendulum experiments. You may already be familiar with these experiments – they gave rise to the popular toy, the Newton's cradle (Figure 12.10.3).

FIGURE 12.10.3 A Newton's Cradle

In one experiment, Newton created pendulums of equal length and mass from metals, glass, sand, and so on. Regardless of substance, the motion and gradual decay of all pendulums was reported by Newton to be identical to within 0.1%. Newton also conducted experiments involving the collision of pendulums. He was able to show the behaviour of their collisions was caused by an action and reaction which were always equal. He noted in these experiments that it was not easy to release the pendulums so exactly that they would collide at the lowermost place AB (Figure 12.10.4) and that errors may also have occurred from unequal density and irregular surfaces.

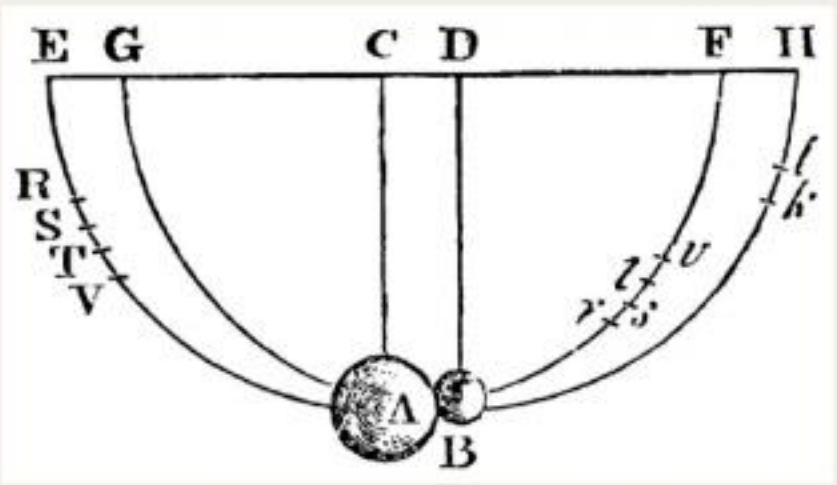


FIGURE 12.10.4 One of Newton's images from the Principia. Newton used this diagram to detail the behaviour of two colliding pendulums.

Newton's work is a brilliant example of the scientific process, where progress is achieved via the contributions of many. Newton's most famous quote (which comes from his worst public dispute with his rival, the scientist Robert Hooke) further demonstrates this:

> "If I have seen further it is by standing on the shoulders of giants."

KEY QUESTIONS

Forming and finding

1. Identify the law of motion Newton evidenced with the colliding pendulum experiments.
2. How did Newton's work contribute to the understanding of Inertia?
3. Find a scientifically credible source which extends your knowledge on Galileo's inclined plane experiments. Acknowledge this source using an appropriate citation.
4. The type of telescope invented by Newton is a reflector telescope. Locate a scientifically credible source which contrasts a refractor telescope with a reflector telescope.

Analysing

5. Identify any examples from the article which evidence that Newton evaluated the reliability and validity of his work.
6. Suggest an improvement or extension to Newton's pendulum experiment which would address the issues Newton Identified.

Road safety and technology

Worldwide, approximately 1.19 million people die from traffic accidents each year. Many more people are injured. One way of reducing the road toll is to design safer vehicles. Modern cars employ a variety of safety features that help to improve the occupants' survival chances in an accident. These include the antilock braking system (ABS), electronic stability control (ESC), inertia-reel seatbelts, variable-ratio-response steering systems, collapsible steering columns, head rests, shatterproof windscreen glass, padded dashboards, front and side air bags, front and rear crumple zones and a rigid passenger compartment. Many of these features are designed to increase the time over which a force acts, to reduce the force on the passengers.

Consider the example of the driver of a car that crashes into a tree at $60\,km\,h^{-1}$ ($16.7\,m\,s^{-1}$). If the driver has a mass of 90 kg, then the change in momentum of the driver as they come to rest is:

$$\begin{aligned}\Delta p &= mu - mv \\ &= (90 \times 16.7) - (90 \times 0) \\ &= 1500\,kg\,m\,s^{-1}\end{aligned}$$

As a result of this collision, the driver will lose all this momentum as the car comes suddenly to a stop. The impulse experienced by the driver is the same, whether the stop is sudden or gradual. In either a sudden or gradual stop, the impulse is equal to the change in momentum: −1500 N s. So, the idea of safety features such as inertia-reel seatbelts, collapsible steering columns, padded dashboards, air bags and crumple zones is not to reduce the size of the impulse, but to reduce the size of the forces that act to bring the driver to a stop. Automotive engineers strive to achieve this by extending the time over which the driver loses momentum.

Crumple zones

A popular misconception among motorists is that cars would be much safer if they were sturdier and more rigid. Drivers often complain that cars seem to collapse too easily during collisions, and that it would be better if cars were structurally stronger and more like an army tank. In fact, cars are specifically designed to crumple to some extent, as shown in Figure 12.11.1. This makes them safer and reduces the seriousness of injuries suffered in car accidents.

Army tanks are designed to be extremely sturdy and rigid vehicles. They can withstand the effect of collisions without suffering serious structural damage. If a tank travelling at $50\,km\,h^{-1}$ crashed into a solid obstacle, the tank would be relatively undamaged. However, its occupants would very likely be killed. This is because the tank has no 'give' in its structure and so the tank and its occupants would stop in an extremely short time interval. The occupants would lose all their momentum in an instant, which means that the forces acting on them would be extremely large. These large forces would cause the occupants of the tank to sustain serious injuries, even if they were wearing seatbelts.

FIGURE 12.11.1 Cars are designed with weak points in their chassis at the front and rear that enable them to crumple in the event of a collision. This extends the time over which the cars come to rest and so reduces the size of the forces acting on the occupants.

Cars today have strong, rigid passenger compartments, but they are also designed with non-rigid sections such as bonnets and boots that crumple if the cars are struck from the front or rear (Figure 12.11.2). The chassis contains parts that have grooves or beads cast into them. In a collision, these beads act as weak points, causing them to crumple in a concertina shape.

This 'concertina' effect allows the front or rear of the car to crumple, extending the time interval over which the car and its occupants come to a stop. This stopping time is typically longer than 0.1 s in a $50\,km\,h^{-1}$ crash. Because the occupants' momentum is lost more gradually, the peak forces that act on them are smaller and so the chances of injury are reduced.

FIGURE 12.11.2 The Australian New Car Assessment Program (ANCAP) assesses the crashworthiness of new cars. This car has just crashed at $50\,km\,h^{-1}$ into a 5-tonne concrete block. The crumpling effect can clearly be seen.

Airbags

The airbags in a car are designed to inflate within a few milliseconds of the occurrence of a collision, to reduce secondary injuries during the collision. The airbags are designed to inflate only when the vehicle experiences an impact with a solid object at 18–20 km h^{-1} or more. The required deceleration must be high, or accidental nudges with another car would cause the airbags to inflate. The car's computer control decides within a few milliseconds to detonate the gas cylinders that inflate the airbags. The propellant detonates and inflates the airbags while, according to the first law of motion, the driver continues to move towards the dashboard. As the driver continues forwards into the airbag, the bag deflates, allowing the body to slow down over a longer time than would otherwise be possible as it moves towards the dashboard (Figure 12.11.3a). The force is minimised, so injury is reduced.

a

b

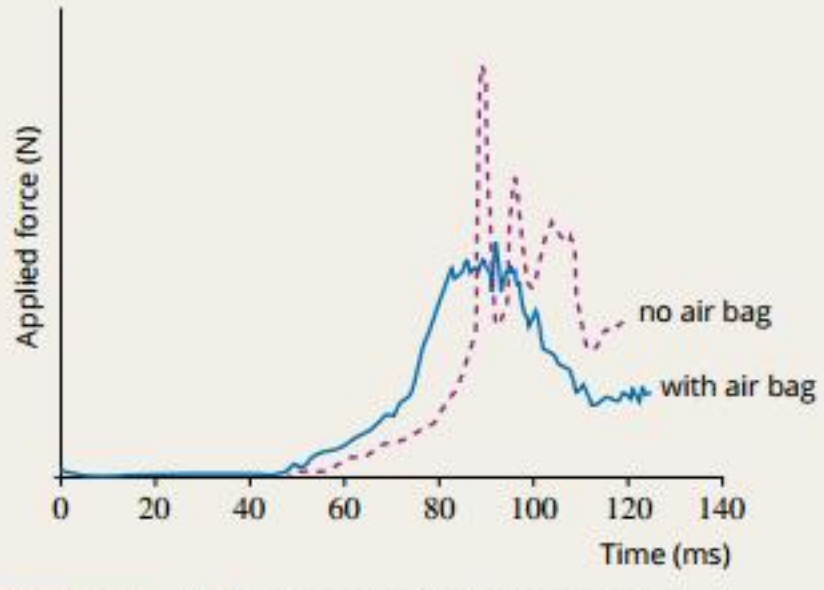


FIGURE 12.11.3 (a) The airbag extends the stopping time and distributes the force required to decelerate the mass of the driver or passenger over a larger area than a seatbelt. (b) The force withstood by the occupant of the car without an airbag is about double that felt with an airbag.

Calculating exactly when the airbag should inflate, and for how long, is a difficult task. Many cars have been crash tested and the results analysed. High-speed film demonstrates precisely why the airbag is so effective. During a collision, only joints and muscles restrain the arms, legs and head of an occupant. Enormous forces are involved because of the large deceleration. The shoulders and hips can, in most cases, sustain the large forces for the short duration. However, the neck is the weak link. Victims of road accidents regularly receive neck and spinal injuries. An airbag reduces the enormous forces the neck must withstand by extending the duration of the collision. This involves the direct application of the concept of impulse. A comparison of the forces applied to the occupant of a car with and without airbags is shown in Figure 12.11.3b.

Airbags prevent the high forces caused by contact of the head with the steering wheel. The airbag ensures that the main thrust of the expansion is directed outwards instead of towards the driver. The airbag's deflation rate, governed by the size of the holes in the rear of the air bag, provides the optimum deceleration of the head for a large range of impact speeds.

The airbag is not the answer to all safety concerns associated with a collision, but it is one of many safety features that form a chain of defence in a collision.

KEY QUESTIONS

Forming and finding

1. Identify the two key variables which safety features can vary while maintaining the same impulse.
2. Explain how an airbag affects the force on the car's occupants.
3. Develop a suitable research question for the investigation shown in Figure 12.11.4.
4. The opening paragraph of the article includes an extensive list of safety features. Select one of these features and locate a credible source which investigates this safety feature.

Analysing

5. A criticism of ANCAP is that it may be wasteful of taxpayer dollars when safety ratings are readily available from other countries. Describe two limitations which international safety rating data may have within the Australian context.
6. ANCAP testing procedures improve over time with technological improvements. Evaluate the validity of comparing the safety rating of a car built in 2001 with one built in 2021.

Monitoring earthquakes and tsunamis

Knowledge of different types of waves and their motion through the ocean and the continents, allows prediction of the possible extent of damage, or the timing of a tsunami.

Monitoring and locating an earthquake

Scientists use their knowledge of seismic waves to determine the epicentre of an earthquake. A seismogram is a sensitive machine that records the arrival time of both P-waves and the S-waves at a seismograph station. The seismogram also records the amplitude of the vibration (Figure 12.12.1). This allows scientists to determine the magnitude of the earthquake.

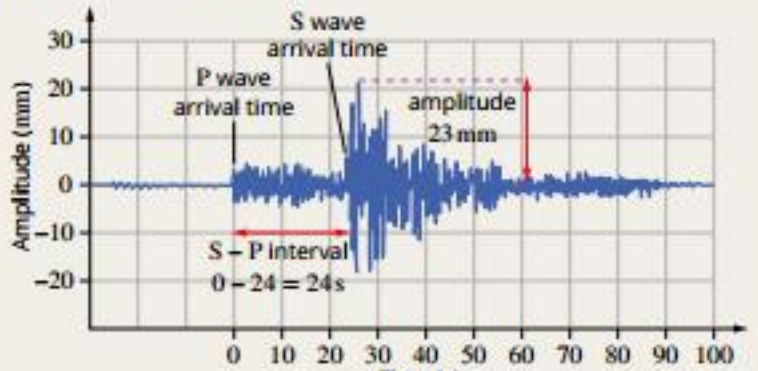


FIGURE 12.12.1 A seismograph showing the difference in time of arrival of P and S seismic waves. Note the amplitude of the strongest wave.

The difference between the arrival times of the S- and P-waves is converted to a distance from the seismograph station in kilometres. An S–P difference of 24 s corresponds with 215 km. A conversion chart also determines the magnitude of the earthquake from the amplitude of the strongest wave. An amplitude of 23 mm corresponds with a magnitude 5.0 earthquake. The Newcastle earthquake in 1989 recorded a magnitude of 5.6 (Figure 12.12.2). The magnitude determines the destructive energy released by the earthquake; it is called the strength of the earthquake. Two other seismograph stations are required to determine the exact epicentre of the earthquake.

Being able to locate the epicentre of an earthquake that occurs in deep oceans allows scientists to predict the possible extent of damage and possibly even warn residents of the possibility of a tsunami.

FIGURE 12.12.2 The epicentre of the 1989 Newcastle earthquake (red dot), a magnitude 5.6 earthquake that caused $4 billion of damage to buildings

Deep-ocean tsunami detection buoys

Deep-ocean tsunami detection buoys (Figure 12.12.3) are one of two types of instruments used by the Bureau of Meteorology. These buoys observe and record changes in sea level out in the deep ocean. This enhances the capability for early detection and real-time reporting of tsunamis before they reach land.

A typical system comprises of a pressure sensor anchored on the sea floor and a surface buoy. The sensor on the sea floor measures the change in height of the water column above by measuring associated changes in the water pressure. This water column height is communicated to the surface buoy and then relayed via satellite to the tsunami warning centre.

The tsunami buoy is triggered into 'event' mode when the pressure sensor first detects the faster-moving seismic wave moving through the sea floor. The system returns to standard mode after four hours if no further seismic events are detected.

Australia's first tsunami detection buoy was deployed on 15 April 2007 in the South-East Tasman Sea, some 1200km from Tasmania. A few more tsunami buoys have since been deployed strategically to protect Australia from tsunami threat due to earthquake sources to the northwest, northeast and southeast of the Australian mainland.

Due to the complexity and uncertainty as to whether an undersea earthquake has the potential to generate a tsunami, the observation of sea levels is a critical factor in verifying whether a tsunami has been generated. The use of actual sea level observations, rather than reliance on seismic observations alone, helps to significantly reduce the risk of false tsunami warnings being issued. All Australian-owned buoys, as well as deep-ocean buoys operated by other countries in the Australian region, provide critical data to Australia's tsunami warning system.

The buoys are just one part of Australia's sea-level observing system, which also includes a number of new and long-standing coastal sea level stations that now have the ability to report sea level variations in real-time to monitor for tsunamis. Combined, these technologies provide a constant stream of sea level data for the Joint Australian Tsunami Warning Centre (JATWC) operated by the Bureau of Meteorology and Geoscience Australia, enhancing tsunami warnings for the Australian public.

FIGURE 12.12.3 A deep-ocean tsunami detection buoy (DART) is deployed in the Tasman Sea.

KEY QUESTIONS

Forming and finding

1. Identify two key features of a seismogram which allow characteristics of an earthquake to be determined.
2. Summarise how a tsunami detection buoy works using a flow chart.
3. Explain how distance affects the ability to issue timely tsunami warnings.
4. As detailed in the article, seismographs are useful for measuring earthquakes to warn about potential tsunamis. Warning about potential earthquakes is achieved with Earthquake Early Warning (EEW) systems and is much more technologically challenging. Find a credible source which details the limitations involved in EEW systems.

Analysing

5. The JATWC uses a network of seismograms, buoys, and sea level monitoring. What impact does this have on the quality of their findings?
6. The article opens with the claim 'Knowledge of different types of waves and their motion through the ocean and the continents, allows prediction of the possible extent of damage, or the timing of a tsunami'. Develop a research question from this claim.

Noise pollution and acoustic design

The world around us is full of unwanted noise, from road noise, air traffic noise, industrial noise and simply noise from other people. These levels of noise are monitored and minimised to avoid unnecessary noise (Figure 12.13.1). Acoustical engineers use their understanding of the behaviour of sound waves to reduce noise pollution and the effects of noise pollution. Reflection, refraction, diffraction and interference of sound waves all need to be considered in designing structures to minimise noise pollution.

One of the most common ways to control noise is with the choice of building materials. Different materials will absorb the energy of the wave by different amounts. The spongier the material, the more it dampens the energy of the sound wave, reducing the amplitude of the wave. This is why insulation or foam can be useful in reducing noise.

FIGURE 12.13.1 Using a sound level meter to measure the noise levels in decibels

Noise transfer also depends on the density of a material. The denser the material, the more energy of the sound wave it will absorb, and the more it reduces the noise level. So, building materials such as brick, thick glass and concrete are quite useful for shielding from and reducing unwanted noise.

A common method used to minimise noise reflection (and transfer) inside a room is to cover the walls (and, if necessary, the floor and ceiling) in foam or other soft structures, which not only reduces reflection of sound but also dampens the sound. These structures are known as sound baffles. An example of this can be seen in Figure 12.13.2. The room is designed to minimise sound reflections or echoes. Notice how the foam is not flat. The foam coating the walls is moulded into pyramids so the waves cannot reflect from the foam as the sharp point disrupts any reflections.

FIGURE 12.13.2 A scientist setting up an experiment in an anechoic (echo-free) chamber. The foam pyramids covering the walls, floor and ceiling absorb the sound waves, preventing echoes or reflections.

To reduce noise, engineers often need to consider and minimise mechanical vibrations which create sound waves. One way to minimise mechanical vibrations, especially with machinery, is to isolate the source of the vibrations. This isolation prevents transmission of the vibrations to other surfaces, which would then also vibrate. Springs, rubber mats and cork are often used to provide this isolation. An example of vibration isolation can be seen in Figure 12.13.3 in which the equipment is specially mounted on isolation blocks to stop the transmission of

any vibrations. The same understanding of wave behaviour is used by acoustical engineers to optimise wanted sound in concert halls (Figure 12.13.4) and cinemas, in railway announcements, and in ultrasound applications such as medicine and non-destructive industrial testing.

FIGURE 12.13.3 A noise-free laboratory at IBM Research. The acoustic dampening panels can be seen on the walls. The equipment is mounted on vibration isolating blocks to isolate it from any vibrations in the room and to isolate the different pieces of equipment from each other.

FIGURE 12.13.4 Modelling concert hall acoustics with a scale model. Laser beams (red) are being used to test the acoustics and find any acoustic defects.

KEY QUESTIONS

Forming and finding

1. List the phenomena associated with sound waves which need to be considered by designers to minimise noise pollution.
2. Explain how isolation reduces the transmission of sound.
3. Identify the key features of sound baffles.
4. In situations where product and environmental design are unable to be modified to reduce noise pollution, workers may instead be required to wear hearing protection. Locate a scientifically credible source which details how a piece of hearing protection works and compare it to the devices mentioned in this article.

Analysing

5. A technology not detailed in the article above is active noise cancelling, which you may be familiar with from modern headphones. This involves the generation of an inverted sound wave to cancel unwanted noise via superposition. Develop a research question around the use of active noise cancellation in the context of noise pollution.
6. Not all sounds are equal. Identify the properties of sound which would need to be considered when researching the efficacy of noise reduction technology.

Development of the wave theory of light

From as long ago as ancient Greek times, scientists have argued about the nature of light and attempted to measure the speed of light.

Aristotle wrote that light was able to travel instantaneously from one point to another. Empedocles, another Greek scientist, disagreed and stated that because light moved then it must take some time, albeit very little, to travel. The question remained unresolved as the technology to measure the speed of light simply did not exist.

In 1667, Galileo Galilei, the Italian scientist and astronomer, attempted to measure the speed of light using lanterns. Two people holding covered lanterns stood on the tops of hills about 1 km apart. The first lantern was uncovered. When the second person saw the flash of light, the second lantern was uncovered. By finding the time between the two observations, the speed of the light between the two observers could be found. However, the distances were too small and Galileo was only able to state that light travelled at least 10 times the speed of sound.

In 1728, James Bradley, an English physicist, used calculations of the apparent change in position of stars due to Earth's orbit around the Sun. His calculations suggested a value of $3.01 \times 10^8 \text{ m s}^{-1}$—incredibly this was within 1% of the value used today, despite relatively rudimentary instrumentation. It was not until the late 1800s that the American scientists Albert Michelson and Edward Morley determined a more accurate value of $2.99910 \times 10^8 \text{ m s}^{-1}$.

Today, the *defined* value for the speed of light in a vacuum is $2.99792458 \times 10^8 \text{ m s}^{-1}$.

This is a constant value in a vacuum throughout the universe (Figure 12.14.1). However, some recent experiments suggest that there may be some special conditions under which light will travel at a different speed.

Mechanical waves need a medium in which to travel. By the end of the 19th century, a transverse wave model for light was accepted but it was believed that like other waves, light needed a medium in which to travel, called the **aether**.

FIGURE 12.14.1 A photo from the Hubble Space Telescope of the illuminated dust shell around an exploding star. Light from this distant source travels at the same speed in a vacuum as it does everywhere else in the universe.

Michelson and Morley had tried without success to find the speed of the Earth as it moved through this aether. Their experiment was designed to measure the speed of light from a star at two different times in the year, 6 months apart. They expected to find a difference in the values they obtained because at one time, the Earth would have been travelling towards the star, and 6 months later the Earth would be on the other side of its orbit, and therefore travelling away from the star.

To do this, Michelson and Morley built what is now called a Michelson interferometer. It essentially consisted of a light source, a half-silvered glass plate, two mirrors and a telescope. The half-silvered glass acts as a beam splitter, allowing some light to pass and reflecting the rest.

The mirrors were placed at right angles to each other and at equal distance from the glass plate, which is oriented at an angle of 45° relative to the two mirrors. The arrangement of an interferometer is shown in Figure 12.14.2.

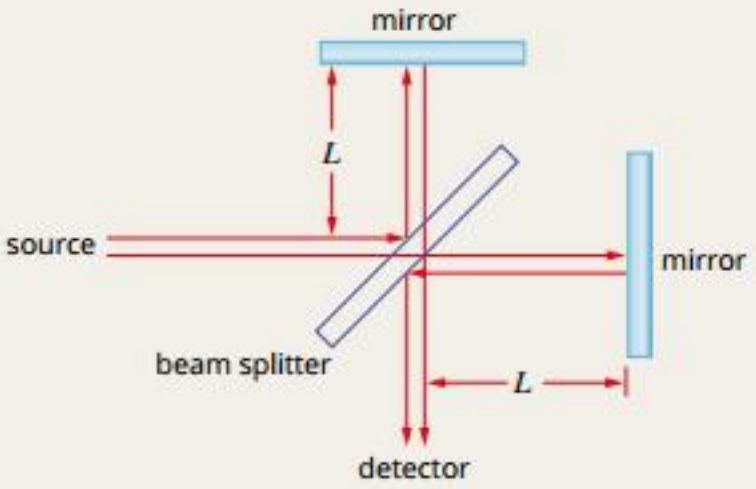


FIGURE 12.14.2 A diagram of the arrangement of the mirrors and beam splitter in the Michelson interferometer

Michelson and Morley were able to measure the speed of light by looking for a change in the interference fringes produced between light that had passed through the two arms of the interferometer. If light travels in the same direction as the aether, it would speed up; if it was travelling in the opposite direction to the aether, its speed would slow down. This means that as Michelson and Morley altered the orientation of the interferometer, the interference pattern produced should also change. Instead, the Michelson–Morley experiment found that there was no effect on the interference patterns produced and it is now one of the most famous failed experiments.

Not only were Michelson and Morley unable to see any effect on the interference patterns produced, they also obtained the same value for the speed of light, regardless of when they took their measurements. That the speed of light was unchanged was considered a strange result. Intuition would suggest that the speed of light from the star relative to Earth should be higher when Earth was moving towards it, and lower as Earth moved away.

To explain the result, it took a tremendous revolution in mechanics in which Newton's mechanics had to be replaced by Einstein's theory of special relativity for fast-moving bodies. Newton's work is now seen as part of a bigger, more encompassing theory.

KEY QUESTIONS

Forming and finding

1 Describe why scientists believed aether was necessary to the theory of light.

2 Distinguish between the transverse model of waves, which was accepted for light in the 19th century, and the longitudinal mode of waves.

3 Explain how Michelson and Morley believed the relative motion of the earth and light would affect their results.

4 There were many other attempts to accurately measure the speed of light such as Fizeau (1849) or Foucault (1862). Find a credible source which details another attempt to determine the speed of light and summarise the process in your own words.

Analysing

5 Describe the limitations present in Galileo's experiment.

6 What major implication did the results of the Michelson–Morley experiment have for future research?

APPENDIX A: Symbols, units and fundamental constants

TABLE 1 The 24 SI prefixes, their symbols and values

Prefix	Symbol	Multiplier	Prefix	Symbol	Multiplier
deca	da	10^{1}	deci	d	10^{-1}
hecto	h	10^{2}	centi	c	10^{-2}
kilo	k	10^{3}	milli	m	10^{-3}
mega	M	10^{6}	micro	μ	10^{-6}
giga	G	10^{9}	nano	n	10^{-9}
tera	T	10^{12}	pico	p	10^{-12}
peta	P	10^{15}	femto	f	10^{-15}
exa	E	10^{18}	atto	a	10^{-18}
zetta	Z	10^{21}	zepto	z	10^{-21}
yotta	Y	10^{24}	yocto	y	10^{-24}
ronna	R	10^{27}	ronto	r	10^{-27}
quetta	Q	10^{30}	quecto	q	10^{-30}

TABLE 2 Some physical constants

Description	Symbol	Value
Unit 1: Thermal, nuclear and electrical physics		
specific heat capacity of ice	c_i	$2.05 \times 10^{3}\,J\,kg^{-1}\,K^{-1}$
specific heat capacity of water	c_w	$4.18 \times 10^{3}\,J\,kg^{-1}\,K^{-1}$
specific heat capacity of steam	c_s	$2.00 \times 10^{3}\,J\,kg^{-1}\,K^{-1}$
latent heat of fusion of water	L_{fusion}	$3.34 \times 10^{5}\,J\,kg^{-1}$
latent heat of vaporisation of water	L_{vapour}	$2.26 \times 10^{6}\,J\,kg^{-1}$
atomic mass unit	u	$1.66 \times 10^{-27}\,kg$
electron volt	eV	$1.60 \times 10^{-19}\,J$
mass of electron	m_e	$9.1093835 \times 10^{-31}\,kg$
mass of proton	m_p	$1.6726219 \times 10^{-27}\,kg$
mass of neutron	m_n	$1.6749275 \times 10^{-27}\,kg$
speed of light in a vacuum	c	$3 \times 10^{8}\,m\,s^{-1}$
charge of electron	e	$-1.60 \times 10^{-19}\,C$
Unit 2: Linear motion and waves		
approximate acceleration due to gravity on Earth	g	$9.80\,m\,s^{-2}$
speed of sound in air (at 25°C)	v_s	$346\,m\,s^{-1}$
Unit 3: Gravity and electromagnetism		
gravitational constant	G	$6.67 \times 10^{-11}\,N\,m^{2}\,kg^{-2}$
mass of Earth	m_E	$5.97 \times 10^{24}\,kg$
radius of Earth	r_E	$6.37 \times 10^{6}\,m$
Coulomb's law constant	k	$9 \times 10^{9}\,N\,m^{2}\,C^{-2}$
permeability of free space (magnetic constant)	μ_0	$4\pi \times 10^{-7}\,T\,A^{-1}\,m$
permittivity of free space	ε_0	$8.85 \times 10^{-12}\,C^{2}\,N^{-1}\,m^{-2}$
Unit 4: Revolutions in modern physics		
Wein's displacement constant	b	$2.898 \times 10^{-3}\,m\,K$
Planck constant	h	$6.626 \times 10^{-34}\,Js$
Rydberg constant	R	$1.097 \times 10^{7}\,m^{-1}$
Boltzmann constant	k	$1.38 \times 10^{-23}\,JK^{-1}$

Processing of data	
percentage uncertainty (%)	$\frac{\text{absolute uncertainty}}{\text{measurement}} \times 100$
percentage error (%)	$\left\lvert\frac{\text{measured value} - \text{true value}}{\text{true value}}\right\rvert \times 100$

Unit 1: Thermal, nuclear and electrical physics

Topic 1: Heating processes

Concept	
first law of thermodynamics	$\Delta U = Q + W$
specific heat capacity	$Q = mc\Delta T$
latent heat	$Q = mL$
energy efficiency	$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$
Celsius to Kelvin temperature scale conversion	$T_K = T_C + 273$

Topic 2: Ionising radiation and nuclear reactions

Concept	
half-life	$N = N_0\left(\frac{1}{2}\right)^n$
logarithms	$\log\left(\frac{1}{2}\right)^n = n\log\left(\frac{1}{2}\right)$
	$\log(xy) = \log(x) + \log(y)$
mass and energy equivalence	$\Delta E = \Delta mc^2$

Topic 3: Electrical circuits

Concept	
current	$I = \frac{q}{t}$
potential difference	$V = \frac{W}{q}$
power	$P = \frac{W}{t}$
resistance in a circuit	$V = IR$
power in a circuit	$P = VI$ $P = I^2R$
resistance in series	$R_t = R_1 + R_2 + \ldots R_n$
resistance in parallel	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$
voltage in a series circuit	$V_t = V_1 + V_2 + \ldots V_n$
current in a parallel circuit	$I_t = I_1 + I_2 + I_3 + \ldots I_n$

Unit 2: Linear motion and waves

Topic 1: Linear motion and force

Concept	
equations of motion with constant acceleration	$v = u + at$
	$s = ut + \frac{1}{2}at^2$
	$v^2 = u^2 + 2as$
momentum	$p = mv$
conservation of momentum	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$
impulse	$\Delta p = F\Delta t$
second law of motion	$a = \frac{F_{\text{net}}}{m}$
work done	$W = \Delta E$ $W = Fs$
gravitational potential energy	$\Delta E_p = mg\Delta h$
kinetic energy	$E_k = \frac{1}{2}mv^2$
conservation of kinetic energy in elastic collisions	$\sum\frac{1}{2}mv^2_{\text{before}} = \sum\frac{1}{2}mv^2_{\text{after}}$
conservation of momentum	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$

Topic 2: Waves

Concept	
wave equation	$v = f\lambda$
frequency	$f = \frac{1}{T}$
Standing waves for a pipe open at both ends or a string fixed at both ends	$L = n\frac{\lambda}{2}$
for a pipe closed at one end or a string fixed at one end	$L = (2n-1)\frac{\lambda}{4}$
Snell's law	$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$
light intensity	$I \propto \frac{1}{r^2}$

Unit 3: Gravity and electromagnetism

Topic 1: Gravity and motion

Concept	
Projectile motion horizontal component of velocity	$v_x = u_x$
horizontal displacement (with no air resistance)	$s_x = u_x t$
final vertical component of velocity	$v_y = u_y + gt$ $v_y^2 = u_y^2 + 2gs_y$
vertical displacement	$s_y = u_y t + \frac{1}{2}gt^2$
force due to gravity (weight)	$F_g = mg$
average speed in circular motion	$v = \frac{2\pi r}{T}$
acceleration in circular motion (centripetal acceleration)	$a_c = \frac{v^2}{r}$
force in circular motion (centripetal force)	$F_c = \frac{mv^2}{r}$
law of universal gravitation	$F = \frac{GMm}{r^2}$
gravitational field strength	$g = \frac{F}{m} = \frac{GM}{r^2}$
third law of planetary motion	$\frac{T_a^2}{r_a^3} = \frac{T_b^2}{r_b^3} = \frac{4\pi^2}{GM}$

Topic 2: Electromagnetism

Concept	
Coulomb's law	$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2} = \frac{kQq}{r^2}$
electric field strength	$E = \frac{F}{Q} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} = \frac{kq}{r^2}$
work done moving a charge in an electric field	$V = \frac{\Delta U}{q}$
magnetic field on a current-carrying wire	$B = \frac{\mu_0 I}{2\pi r}$
magnetic field inside a solenoid	$B = \mu_0 nI$
magnetic force on a moving charged particle	$F = qvB\sin\theta$
magnetic force on a current-carrying wire	$F = BIL\sin\theta$
magnetic flux	$\Phi = BA\cos\theta$
electromagnetic induction: induced emf in coils	$\text{emf} = -\frac{N\Delta(BA_\perp)}{\Delta t}$ $\text{emf} = -N\frac{\Delta\Phi}{\Delta t}$
power in transformers	$I_p V_p = I_s V_s$
voltage in transformers	$\frac{V_p}{V_s} = \frac{N_p}{N_s}$

Unit 4: Revolutions in modern physics

Topic 1: Special relativity

Concept	
time dilation	$t = \frac{t_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$
length contraction	$L = L_0\sqrt{\left(1 - \frac{v^2}{c^2}\right)}$
relativistic momentum	$p_v = \frac{m_0 v}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$
mass–energy equivalence	$\Delta E = \Delta mc^2$

Topic 2: Quantum theory

Concept	
Wien's law	$\lambda_{max} = \frac{b}{T}$
photon energy	$E = hf = \frac{hc}{\lambda}$
photoelectric effect	$E_k = hf - W$ $W = hf_0$
de Broglie wavelength	$\lambda = \frac{h}{p}$
Bohr's model of the atom and atomic energy states	$mvr = \frac{nh}{2\pi}$ $n\lambda = 2\pi r$
Rydberg formula	$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$

Topic 3: The Standard Model

Concept	
conservation of baryon number	$B = n_b + n_{\bar{b}}$ $B = \frac{1}{3}(n_q - n_{\bar{q}})$
conservation of lepton number	$L = n_l + n_{l'}$

Group

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.01																	2 He 4.00
2	3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.91	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30
6	55 Cs 132.91	56 Ba 137.34	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Ds (271)	111 Rg (272)	112 Cn (277)	113 Nh (284)	114 Fl (289)	115 Mc (288)	116 Lv (293)	117 Ts (294)	118 Og (294)

1 ← Atomic number
H ← Symbol
1.01 ← Relative atomic mass*

Lanthanides

58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97

Actinides

90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

Every isotope of these elements is radioactive.

*Brackets indicate the relative atomic mass of the isotope with the longest half-life.

Glossary

A

aberration A distortion of an image due to a physical property of the image-forming apparatus.

absolute refractive index An index or number that is equal to the ratio of the speed of light in a vacuum compared with the speed of light in a medium.

absolute zero The coldest possible temperature (0 K, −273.15°C).

absorption The taking up and storing of energy, such as radiation, light or sound, without it being reflected or transmitted. During absorption, the energy may change from one form into another. When radiation strikes the electrons in an atom, the electrons move to a higher orbit or state of excitement by absorbing the energy of the radiation.

acceleration rate of change of velocity of an object (symbol, a; SI unit m/s^2).

aether The theoretical medium that was once supposed to fill space to support the propagation of light modelled as a wave.

air resistance The frictional force that acts against moving objects as they travel through the air. Air resistance always acts in the opposite direction to the motion of an object.

alpha particle The composite particle consisting of two protons and two neutrons bound together, emitted from the nuclei of some radionuclides. Its symbol is ${}^4_2\text{He}$ or ${}^4_2\alpha$.

alpha radiation Occurs when a radioactive nucleus emits an alpha particle.

ammeter An instrument that measures electric current flowing through a circuit, in amperes.

amplitude The maximum displacement of a particle from the average or rest position.

angle of incidence The angle measured between the incident ray and the normal to the surface that it strikes.

angle of reflection The angle between the reflected ray and the normal to the surface that it strikes.

antineutrino An almost massless particle associated with beta negative decay.

antinode An area in a standing wave where the amplitude of the wave is at its maximum.

aperture A very narrow opening or gap.

apparent depth The apparent distance of the virtual image from the surface of the water.

artificial transmutation The changing of one isotope into an isotope of another element during radioactive decay and during neutron bombardment in a nuclear reactor (distinct from natural radioactivity) (e.g. neutron bombardment of ^{235}U).

atom The smallest unit of matter that still behaves as a chemical element. It consists of a positively charged nucleus, comprised of positively charged protons and neutral neutrons, surrounded by negatively charged electrons.

atomic number The number of protons in an element's nucleus.

B

beta particle A particle emitted during beta negative or beta positive decay. It is an electron in beta negative decay, and a positron in beta positive decay.

beta negative radiation A form of radioactive decay – an energetic electron (${}^0_{-1}\text{e}$) and associated antineutrino (${}^0_1\overline{\nu}$) are emitted from an atomic nucleus (symbol β^-).

beta positive radiation A form of radioactive decay – an energetic positron (${}^0_1\text{e}$) and associated neutrino (${}^0_0\nu$) are emitted from an atomic nucleus (symbol β^+).

binding energy Energy required to split a nucleus into its separate nucleons.

binding energy per nucleon The binding energy divided by the number of nucleons in the nucleus of an atom.

C

calorimetry The science of measuring amounts of heat.

centre of curvature The centre of the spherical mirror from which the mirror is assumed to have been made.

centre of mass Point at which the mass of an object is considered to be concentrated for the purpose of analysing motion.

chain reaction A single nuclear reaction that causes a rapid increase in the number of subsequent reactions.

charge A characteristic of a unit of matter that refers to the extent to which a particle has fewer or more electrons than protons.

collinear Lying on the same straight line.

collision A collision occurs when two or more objects hit each other due to forces acting on them, resulting in an exchange of energy or momentum.

compression Area of high pressure in a wave.

concave A shape that is inwardly curved.

conduction The movement of energy (such as heat) from one object to another without the net movement of particles (atoms or molecules).

conductor A substance, body or system that readily conducts heat, electricity, sound or light; a material that allows the flow of electric charge.

conserved When a quantity that exists before an interaction is exactly equal to the quantity that exists after the interaction.

constructive interference The process where two or more waves combine or superpose to reinforce each other. This occurs where the displacement of the individual waves is in the same direction so the amplitude is increased.

contact forces The forces that exist when one object or material is touching another. Friction, drag and normal reaction forces are contact forces.

convection The movement caused within a fluid by the tendency of hotter and less dense material to rise, and colder, denser material to sink under the influence of gravity, which results in transfer of heat.

conventional current The current that moves in the same direction as positive charge flow.

convex A shape that is outwardly curved.

corpuscular Particle-like in nature.

coulomb The SI unit of electric charge.

coulomb force The attractive (for particles of opposite charge) or repulsive (for particles of the same charge) force that exists between charged particles over a distance.

crest The highest point of a wave.

critical angle The angle of incidence that produces an angle of refraction of 90°.

critical mass The amount of material needed to sustain a nuclear fission chain reaction.

current The flow of electric charge.

current law of circuits (Kirchhoff's current law) The sum of all currents flowing into a node in an electrical circuit equals the sum of currents flowing out of the node.

D

daughter nucleus The resulting nuclide formed after the parent nucleus has decayed.

decay The spontaneous emission of radiation from a nucleus via alpha, beta or gamma radiation. It is distinct from nuclear fission.

decay series The successive decay products of daughter nuclides produced until a final stable nuclide is formed.

destructive interference The process in which two or more waves combine or superimpose to reduce the amplitude. This occurs where the displacement of the individual waves is in the opposite direction.

diffraction The process affecting light and other wave forms that causes a wave to spread out as it passes through a narrow aperture or past an edge.

diffuse reflection When light is reflected from a rough or uneven surface and is scattered in all directions.

dimension Space can be considered to consist of three length dimensions. The position of an object can be defined in relation to its position along each of the three dimensions. Typically, these three dimensions are labelled x, y and z. However, up–down, left–right and backwards–forwards are also appropriate.

dimensional analysis The use of the units in a graph or formula to check that the derived term is correct.

direction conventions Direction conventions are standardised systems for describing the direction in which an object is travelling. The use of cardinal points of a compass (N, S, E and W) is an example of a direction convention.

dispersion (of light) On refraction, different colours of light will take slightly different paths. This results in the spreading out of white light into its component colours. This is known as dispersion.

displacement An object's change in position, relative to its starting position and final position. Displacement does not consider the route the object took to change position, only where it started and where it ended. Displacement is a vector quantity. It is measured in metres (m) and given the symbol s.

dissipate To lose or waste something, to melt away or to cause it to disappear.

distance travelled How far an object travels during a particular motion or journey between the origin and the destination point. Distance is a scalar value. Direction is not required when expressing magnitude (symbol, d; SI unit, m).

drift velocity The average velocity of an electron in a material through which it is travelling.

E

efficiency The percentage of energy that is effectively transformed by a system.

elastic collision A collision in which both momentum and kinetic energy are conserved.

elastic modulus The resistance of a material to being deformed elastically; the stiffer a material, the higher its elastic modulus.

electrical circuit A path in which electrons form a voltage or current source flow.

electrical potential energy Potential energy due to the separation of charge in part of an electric circuit. The energy is stored in the electric field.

electricity The energy that results from the movement of charged particles.

electromagnetic radiation A wide range of frequencies (or wavelengths) that can be created by accelerating charges, resulting in a rapidly changing magnetic field and electric field travelling out from the source.

electromagnetic spectrum The family of electromagnetic radiations consisting of radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays. All electromagnetic radiations travel at $3.00 \times 10^8\,\text{m}\,\text{s}^{-1}$ in a vacuum.

electromagnetic waves Produced by an oscillating charge resulting in mutually perpendicular electric and magnetic fields.

electron The negatively charged subatomic particle (symbol is ${}^{0}_{-1}\text{e}$ or ${}^{0}_{-1}\beta$).

electronvolt A unit of energy equal to the work done on an electron in accelerating it through a potential difference of one volt (unit, eV).

electrostatic attraction Occurs when unlike charged particles attract; or example, when the positively charged proton is attracted to the negatively charged electron.

electrostatic force See *coulomb force*.

electrostatic repulsion Occurs when like charged particles repel; for example, when a positively charged proton repels another positively charged proton.

elementary charge The charge carried by one electron or one proton.

emission Something that is emitted or given out.

emit To give out. For example, energy can be emitted in the form of heat, light, radio waves etc.

energy conservation A principle in physics that states that the total energy in an isolated system remains constant. Energy cannot be lost or removed but it can transform from one type of energy to another; for example, from mechanical energy to heat and/or sound energy.

equilibrium The condition of equal balance between opposing forces acting on each other; so that a static or balanced situation results.

equivalent resistance A single resistance that could be used to replace a number of individual resistors for the purpose of circuit analysis.

evaporation The changing of a liquid into a gas, often under the influence of heat (as in the boiling of water) but not necessarily requiring heating.

explosion In an explosion, an object will break apart into multiple fragments, each with their own momentum.

extend To extend an experiment means to adjust the methodology to explore new aspects or gain deeper insight into the phenomena observed in the initial experiment.

F

first harmonic The smallest or lowest of the frequencies for a given length of string or pipe; also known as the fundamental frequency.

first law of motion States that an object will maintain a constant velocity unless an unbalanced, external force acts on it.

fissile Capable of undergoing nuclear fission after capturing low-energy neutrons.

fission fragments The nuclides that are formed via the process of nuclear fission.

focal length The distance from a lens or mirror at which a parallel beam of light is brought to a focus.

force A vector quantity which measures the magnitude and direction of a push or a pull. It is measured in newtons (N).

free-fall The motion of a falling body under the effect of gravity only; no air resistance or propulsive forces are acting.

frequency Equal to the number of waves that move past a given point in one second (symbol, *f*; SI unit, Hz).

fundamental The lowest and simplest form of standing wave vibration, with one node and one antinode.

G

gamma radiation Extremely high-frequency electromagnetic radiation emitted from the nucleus of some radionuclides (symbol is γ).

geometrical optics The branch of optics that models the path of light using straight rays.

gravitational potential energy Energy stored in the gravitational field due to an object's position in the gravitational field. Measured in joules (J).

H

half-life The time taken for half of the nuclei of a radioactive isotope to decay.

harmonic A frequency that is a whole number multiple of the same basic frequency.

heat The energy transferred from one system to another because of a difference in temperature.

Huygens' principle States that every point on a wavefront is a source of secondary wavelets. These wavelets spread out in the forward direction at the same speed as the source wave. The new wavefront is a line that is a tangent to all of these wavelets.

I

image The location in space from which all the reflected light appears to diverge. An optically formed reproduction of an object by using a lens or a mirror.

impulse The change in momentum of an object is also called the impulse of an object. The impulse is calculated by the final momentum minus the initial momentum.

in phase Two points within a wave that are simultaneously experiencing the same displacement and velocity and are, therefore, moving in the same direction.

incident To arrive at or strike a surface, especially a beam of light or radiation, or particles.

incident ray A ray of light that hits a surface of any material.

induction The process by which an object becomes electrically charged by being exposed to another object with an excess of either positive or negative charge.

inelastic collision A collision in which kinetic energy is not conserved.

inertia A property of an object, related to its mass, that opposes changes in motion.

insulator A material or an object that does not easily allow heat, electricity, light or sound to pass through it. Air, cloth and rubber are good electrical insulators. Feathers and wool are good thermal insulators.

intensity The average rate of flow of energy per unit area.

intensity (of a wave) The average rate of flow of energy per unit area.

interference This occurs when two or more waves occupy the same place at the same time. The resultant displacement of the wave particles is the vector addition of the amplitudes of the individual waves.

interference pattern The pattern due to light (or fast-moving particles) from two or more sources arriving at the one location.

internal energy The total potential energy and kinetic energy of the particles in a system.

internal resistance The resistance of a component in a circuit such as a battery, voltmeter or ammeter. For Physics Units 1 and 2 this is usually assumed to be ideal.

inverse square law A mathematical pattern expressing a relationship in which one quantity decreases with the square of another; e.g. if the first doubles, the second decreases to one-quarter, and so on.

ion An atom with unbalanced charges, making it either more positive or more negative.

ionisation The process by which an atom acquires a negative or positive charge by gaining or losing electrons.

ionised An atom or molecule becomes electrically charged.

ionising radiation Radiation that is energetic enough to cause ionisation. Examples include ultraviolet light, X-rays, gamma rays, alpha particles, beta particles and neutrons.

isotope A chemical element that has the same atomic number but different neutron number.

J

junction A point in an electric circuit that current can flow into or out of from more than one direction.

K

kelvin The SI unit of temperature measurement on the absolute temperature scale based on the triple point of water.

kinetic energy The energy resulting from the movement of an object. When associated with temperature, kinetic energy is associated with the motion of particles in a substance (symbol, E_k; SI unit, J).

kinetic particle model A model in which matter is made up of particles that are constantly moving.

L

law A statement describing invariable relationships between phenomena in specified conditions.

law of conservation of electric charge The total electric charge of an isolated system remains constant regardless of changes within the system.

law of conservation of energy The energy in a system before an interaction is exactly equal to the energy in the system after the interaction.

law of reflection States that the angle of reflection, measured from the normal, equals the angle of incidence measured from the normal.

lens A piece of transparent material that has been shaped so that the light passing through it will bend in a particular way.

longitudinal wave A longitudinal wave is one in which the vibration of the particles within the medium are parallel to the direction of energy flow of the wave.

M

magnification The factor by which the size of an image has changed from the size of the original.

magnitude The size or extent of something. In physics, this is usually a quantitative measure expressed as a number of a standard unit.

mass defect The change in mass of the reactants to the products of a nuclear reaction. The mass defect is converted to energy.

mass number The number of nucleons (protons and neutrons) in a nucleus.

Maxwell–Boltzmann distribution A graph of kinetic energy against number of particles that shows the range of energies in a sample of a gas or a liquid at a given temperature.

mechanical energy The sum of the kinetic energy of an object and all potential energies available to it (e.g. gravitational, spring, chemical).

mechanical wave A wave that transfers energy through a medium.

mechanical work The transfer of energy to or from an object by the action of a force over a distance.

medium A physical substance, such as air or water, through which a mechanical wave is propagated and energy is transmitted.

metal A material made up entirely of metal atoms and is electrically conductive.

model In science, a representation that describes, simplifies, clarifies or provides an explanation of the workings, structure or relationships within an object, system or idea.

modify Change the form or qualities of.

momentum The product of an object's mass and velocity.

multimeter A meter than can be used in an electrical circuit as either an ammeter or a voltmeter, depending on how it is wired.

N

natural frequency The frequency at which an object will tend to vibrate when disturbed.

net charge The total number of positive and negative charges in an atom or molecule.

net force The vector sum of all the individual forces acting on a body. This is also known as the resultant force.

neutral The state of having no charge.

neutrino An almost massless particle associated with beta positive decay.

neutron An uncharged subatomic particle found in the nucleus.

neutron number The number of neutrons in a nucleus (symbol, N).

newton The SI unit for force (N).

node The point in a medium that is not displaced as a wave is propagated through it.

non-contact forces The forces that act at a distance and do not require the bodies to touch each other. Gravitational, magnetic and electric forces are non-contact forces.

non-metal A material made up entirely of non-metal atoms and is electrically insulative.

non-ohmic A conductor that does not follow Ohm's law; the relationship between voltage and current is non-linear.

normal An artificially constructed dashed line drawn perpendicularly from the boundary surface.

nuclear fission The process in which a large unstable nucleus splits, forming two (or more) smaller, more stable nuclei and releasing neutrons and energy.

nuclear fusion A nuclear reaction in which two or more atomic nuclei combine to form one or more different, heavier atomic nuclei and subatomic particles.

nuclear reaction An interaction where a target nucleus and a smaller particle collide.

nuclear reactor A device used to start and continue a nuclear reaction.

nuclear transmutation The process by which a nuclide changes its atomic number; that is, changes into a different element.

nucleon A particle (protons and neutrons) that makes up the nucleus of an atom.

nucleus The central part of an atom.

nuclide The range of atomic nuclei associated with a particular atom, which is defined by its atomic number and the various isotopes of that atom as identified by the mass number.

O

object A point or source of outgoing rays.

ohmic A conductor that follows Ohm's law; the relationship between voltage and current is linear.

optical density A measure of the speed at which light is able to travel through a substance.

P

P-wave A longitudinal seismic wave, also called a primary wave.

parallel circuit A circuit that contains junctions; the current drawn from the battery, cell or electricity supply splits before it reaches the components and re-joins afterwards.

parent nucleus The radionuclide that undergoes decay.

particle accelerator A device used to accelerate and hold charged particles at high speed, usually using electric and magnetic fields. The particles are then typically smashed together.

particles A small portion, or piece, of matter.

path difference The difference in distance travelled by two waves. This is useful in determining the phase difference between two waves travelling at the same velocity with the same frequency.

penetrating ability The distance that radiation can travel into a substance before being absorbed into the substance.

period The time interval for one vibration or cycle to be completed.

phase A particular point in time of a wave. Points on the wave separated by 360°, or a complete cycle, are in phase. Points on a wave separated by 180° are out of phase.

phase change Occurs when waves that reflect off fixed barriers are inverted, or have a 180° phase change.

phenomenon An event that is not artificial and can be observed through the senses or can be scientifically described or explained.

plane polarised Polarisation in which the electric vector of waves of light or other electromagnetic radiation is restricted to vibration in one plane.

plane wave A wave of constant frequency and amplitude with wavefronts that are long straight lines.

polarised light Light waves that have their electric fields aligned, i.e. varying in the same plane as one another.

polarising filters A filter that is able to convert unpolarised light into polarised light.

position The location of an object with respect to a reference point. Position is a vector quantity.

positron A positively charged electron.

potential difference The difference of electric potential between two points; measured in volts.

potential energy Energy that can be considered to be 'stored' within a body due to its position, composition or molecular arrangement.

power The rate at which work is done (symbol, P; SI unit, W).

principal axis The line drawn through both the optical centre and the centre of the curvature of a lens.

principal focus (principal focus point) The point of a convex lens at which the rays parallel to the principal axis converge (are brought together) to a focus.

principle of superposition The resultant displacement is the sum of the individual wave displacements at a point.

propagation The motion of waves through or along a medium.

proton A positively charged subatomic particle.

pulse A single disturbance moving through a medium from one point to the next.

R

radiation The emission of energy as electromagnetic waves or as moving subatomic particles, especially high-energy particles, which cause ionisation.

radioactive Something that spontaneously emits radiation in the form of alpha particles, beta-plus or beta-minus particles, and/or gamma rays.

radioactivity The process by which an unstable nucleus with excess energy loses some of that energy by emitting radiation in the form of electromagnetic waves or moving subatomic particles.

radioisotope A radioactive isotope.

radionuclide A radioactive nuclide.

radius of curvature The radius of the sphere from which a mirror has been cut.

rarefaction An area of decreased pressure within a longitudinal sound wave.

ray An artificially constructed line, drawn perpendicular to the wavefront, in the direction of energy transmission or transfer.

ray tracing The process of using known pathways of light to model image formation on a scaled, two-dimensional diagram.

Rayleigh wave A seismic surface wave causing the ground to shake in an elliptical motion.

real depth The actual distance of an object beneath the surface of the water, as would be measured by submerging a ruler along with it.

real image An image that is formed at the point of intersection of light from a common point of origin.

real position The actual position of an object.

rectilinear The description of motion in a straight line.

rectilinear propagation The property of waves to move in a straight line through a uniform medium.

redirect To redirect an experiment means to adjust the methodology to explore new aspects or gain deeper insight into the phenomena observed in the initial experiment.

refine To refine an experiment means to adjust the methodology for greater accuracy or precision, often leading to more investigable research questions.

reflection To change the direction of a wave as it strikes a surface and is bounced back.

refracted ray A ray of light that has entered a medium and either bent towards or away from the normal, depending on the density of the new medium.

refraction The bending of the direction of travel of a ray of light, sound, or other wave as it enters a medium of differing refractive index (optical density).

relative refractive index An index or number that is allocated to each pair of substances indicating their relative optical densities.

resistance A measure of how much an object or material resists the flow of current; the ratio of the potential difference across a circuit component and the current flowing through it: $R = V/I$. Resistance is measured in ohms (Ω).

resistor A component that restricts or impedes the flow of electric current.

resolution The measure of an instrument's ability to separate two points. It is called the resolving power of an instrument.

resonance The state of a system in which an abnormally large vibration is produced in response to an external vibration. Resonance occurs when the forcing frequency is the same, or nearly the same, as the natural vibration frequency of the system.

resonant frequency A natural frequency of vibration determined by the physical parameters of the vibrating object.

resultant One vector that is the sum of two or more vectors.

resultant force A force that is also known as the net force.

S

S-wave A transverse seismic wave, also called a secondary wave.

scalar A physical quantity that is represented by magnitude and units only. Mass, time and speed are examples of scalar quantities.

scientific journal A book containing the entire collection of work related to an experiment or investigation.

second law of motion States that force is equal to the rate of change of momentum. This can be processed mathematically to: the acceleration of an object is directly proportional to the force on the object and inversely proportional to the mass of the object.

Segre plot A graph showing how the neutron number of nuclides changes with atomic number. It shows stable nuclides and radioactive nuclides and is useful in determining how a nuclide will react.

series circuit A circuit in which the components are connected one after another in a continuous loop so that the same current passes through each component.

sinusoidal oscillation A disturbance with a period oscillation and a fixed frequency. The term comes from the mathematical sine function.

specific heat capacity The amount of energy that must be transferred to change the temperature of 1 kg of a material by 1°C or 1K. (symbol, c; SI unit, $Jkg^{-1}K^{-1}$).

specific latent heat The 'hidden' energy used to change the state of a substance at the same temperature; the energy is not seen as a change in temperature.

specific latent heat of fusion The energy required to change 1 kg of solid to a liquid at its melting point.

specific latent heat of vaporisation The energy required to change 1 kg of liquid to a gas at its boiling point.

speed The ratio of distance travelled to time taken. Speed is a scalar quantity.

spherical mirror A mirror that has a specially shaped surface such that it could have formed part of the surface of a sphere.

standing wave Waves with stationary vibration pattern formed due to the superposition of waves with particular frequencies.

strong nuclear force A short-range but powerful force of attraction that acts between all the nucleons in the nucleus. The strong nuclear force acts on quarks and binds them together in hadrons. It also acts to bind protons and neutrons together within atomic nuclei.

subatomic A scale smaller than the atom.

superposition When two or more waves overlap in space, the resultant wave is the algebraic sum of the individual waves.

surface waves A seismic wave that travels across the surface of the Earth as opposed to through it.

T

temperature A measure of the average translational kinetic energy of the particles in a substance. Temperature can be measured in degrees Celsius (°C) or kelvin (K).

theory In science, a set of concepts, claims and/or laws that can be used to explain and predict a wide range of related observed or observable phenomena.

thermal contact When two objects are in contact so that energy exchange via heat transfer is possible.

thermal energy The internal energy present in a system due to its temperature (symbol, U; SI unit, J); transfer of thermal energy when heating or cooling a substance has the symbol Q in the equation $Q = m\Delta T$.

thermal equilibrium For two bodies in thermal contact, the condition in which the two reach the same temperature and there is no further net transfer of thermal energy.

thermal inversion A situation in which a layer of warm air lies over a layer of cool air in the Earth's atmosphere.

thermodynamics The study of heating processes and their relationships with various forms of energy and work; concerned with characteristics of energy such as temperature, entropy and pressure and their interrelationships.

third law of motion States that for every action (force), there is an equal and opposite reaction (force).

torsional wave A twisting type of wave.

total internal reflection Occurs when the angle of incidence exceeds the critical angle for refraction. Light or waves are reflected back into the medium; there is no transmission of light.

transfer The movement of energy from one place to another.

transform To change energy from one form to another (e.g. from gravitational potential to kinetic).

transmitted A wave or pulse carries energy through a medium from one location to another.

transmutation The process in which an isotope changes into an isotope of another element (usually from natural decay).

transverse wave A wave where the direction of oscillation of particles is perpendicular to the direction of energy transfer.

travelling wave A wave in which its maxima and minima are moving through the medium in which the wave is travelling.

trough The maximum negative displacement reached when particles in a transverse wave are displaced downwards from the average position, or resting position.

tsunami A large wave on the ocean caused by an undersea earthquake, or a volcanic eruption, or a coastal landslide.

U

unified atomic mass unit A unit of mass used for very small masses (unit, u) equal to 1.66×10^{-27} kg.

units The properties related to physical measurements. Units can be fundamental, such as metres (m), seconds (s) or kilograms (kg). Units can also be derived by combining fundamental units such as metres per second (ms^{-1}).

unpolarised light The light waves that have electric field variations that are not aligned with one another.

V

vector A physical quantity that requires magnitude, units and a direction in order to be fully defined. Velocity, acceleration and force are examples of vector quantities. A vector may be represented pictorially by an arrowed line segment ($\rightarrow$) and symbolically as a or $\underrightarrow{a}$.

vector diagram A diagram that depicts the direction and relative magnitude of a vector quantity by a vector arrow.

velocity The ratio of displacement to time taken. Velocity is a vector quantity. The SI unit for velocity is ms^{-1}.

velocity (average) The rate of change of displacement calculated using the formula

$$\text{velocity} = \frac{\text{displacement}}{\text{time}}$$

velocity (instantaneous) The rate of change of displacement measured at an instant in time.

virtual image An image formed when light rays that originate from a common point on an object are diverged by a mirror or lens and appear to have come from a common image point.

visible light The range of electromagnetic radiation frequencies to which the cells in human eyes can respond.

volatile The liquids that have weak surface bonds and so evaporate rapidly.

voltage law of circuits (Kirchhoff's voltage law) The energy inputs in a circuit equal the sum of energy output from loads in the circuit such that the directed sum of the electrical potential differences around any closed network is zero.

voltmeter An instrument that measures potential difference, which is the voltage change between two points in a circuit in volts.

volt The SI unit of potential difference or voltage.

W

wavefront A continuous line or surface that includes all the points reached by a wave or vibration at the same instant as it travels through a medium.

wavelength The distance between one peak or crest of a wave of light, heat or other energy and the next corresponding peak or crest (symbol, λ; SI unit, m).

work A concept that relates force to energy; defined as the product of a force and the displacement of an object on which it acts.

work–energy theorem The work done on an object by a net force is equal to the change in the kinetic energy of the object.

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